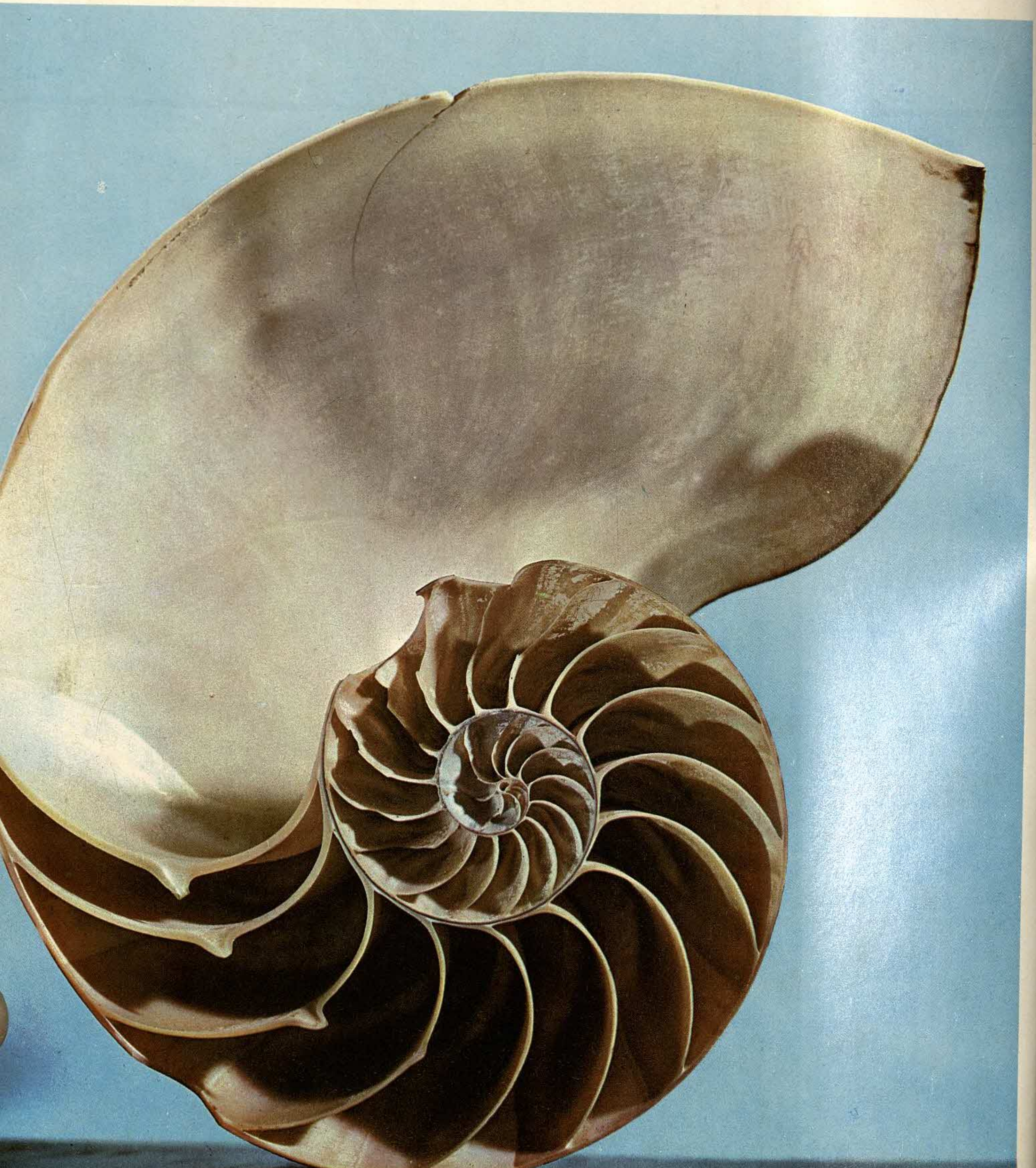
5

Illustrated World of Science Encyclopedia

Earth Science II:
EVOLUTION:
FROM FOSSIL
TO FISH

THE WORLD OF SCIENCE



A NAUTILUS SHELL—The animal lived in the large chamber at the top; numerous partitions below formed the phragmocone.

THE WORLD OF SCIENCE

VOLUME

5

EARTH SCIENCE II

EVOLUTION: From Fossil to Fish

with

The Illustrated Science Dictionary

CREATIVE WORLD PUBLICATIONS, INC.
CHICAGO

Copyright © 1971 by CREATIVE WORLD PUBLICATIONS, INC.
Illustrations copyright © 1966 by Fratelli Fabbri Editori.

THE WORLD OF SCIENCE ENCYCLOPAEDIA has been translated and adapted from SCIENZA: ENCICLOPEDIA TECNICA E SCIENTIFICA by Fratelli Fabbri Editori, Milan, Italy.

THE ILLUSTRATED SCIENCE DICTIONARY, copyright © 1971 by F. E. Compton Co., appears with full permission of the publisher, F. E. Compton Co., Chicago, Illinois.

All rights—including but without limitation copyright of text, drawings or any part of them, and the copyright of translations into any language—are reserved to the copyright proprietors.

No part of this work may be reproduced or utilized in any form by any means, electronic or mechanical—including but without limitation photocopying, recording, or by any information storage and retrieval system—without permission in writing from the copyright proprietors.

Library of Congress Catalog Card Number: 71-139118

Typesetting primarily by SSPA Typesetting, Inc., Carmel, Indiana
Filmwork by Widen Engraving Co., Madison, Wisconsin
Printed and bound in U.S.A. by W. A. Krueger Co., Brookfield, Wisconsin

VOLUME 5

EARTH SCIENCE II
EVOLUTION: From Fossil to Fish

7 Fossil Remains
10 How Fossils Are Formed
13 Plant Fossils
16 The History of Evolutionary Theory
19 Adaptation and Selection
22 Evolution of Species
24 Phylogeny
26 Precambrian Time
28 The Archaeozoic Era
31 Specialization for Survival
34 The Late Precambrian Era
37 The Paleozoic Era
40 The Cambrian Period
43 The Spread of the Invertebrates
47 The Ordovician and Silurian Periods
49 From One Cell to Many Cells
52 The Sponge
55 Fauna of the Ordovician and Silurian Periods
58 The Echinoderms
61 Ancient Ancestors of Man
63 The Long History of the Sea Urchins
64 Animal Life Conquers Dry Land
66 The Devonian Period
68 Fauna of the Devonian Period
70 The Devonian Scene
72 The Plant Kingdom
75 The Early Evolution of Terrestrial Plants
77 The Origin of the Vertebrates
81 Chemical Fossil Substances
84 Paleobiochemistry
87 Locomotion in Water
90 The Ammonites
95 The Carboniferous Period
99 Fauna of the Carboniferous Period
102 Flora of the Carboniferous Period
104 The Distribution of Carboniferous Flora
108 The Cephalopods
113 The Permian Period
116 The Pelecypods
119 Permian Fauna
122 The Mesozoic Era
124 The Mollusks
127 The Triassic Period
129 Microfossils
131 Fauna of the Triassic Period
133 Flora of the Triassic Period
136 The Jurassic Period
139 The Geology of the Jurassic Period
141 Fauna of the Jurassic Period
145 Higher Animals
148 Flora of the Jurassic Period
150 The Chordates
152 Primitive Fish
156 The Amphibians
160 Abbreviations and Symbols
161 *Illustrated Science Dictionary* (conjugation *to* deferent)

VOLUME 5

EARTH SCIENCE II

EVOLUTION: From Fossil to Fish

INTRODUCTION

For centuries, philosophers and scholars have speculated about the origin and development of the Earth and about the history of life on the Earth. Their ideas were often closely tied to religious thinking and, for the most part, early studies were more theologic than scientific. By the eighteenth century, scholars began to recognize that fossils (from the Latin *fossilis* meaning "something dug out of the mud") were the remains of plants and animals preserved in rocks.

The birth of modern geology can be tied to the early studies of fossils. In the first few articles of this volume, the reader will be introduced to *what* a fossil looks like (it can be as spectacular as the frozen carcass of a woolly mammoth or as obscure as a microscopic fragment of a pollen grain), *how* fossils demonstrate the mechanism and direction of biologic evolution, and *when* fossils first appear in the geologic record.

Fossils, then, provide the key needed to study the geologic and biologic history of the Earth. Opening the door to the geologic past, however, requires more than simply cataloging and describing fossils; the scientist has to understand the relationship between fossils and rocks. In the early 1800s, an English surveyor named William Smith demonstrated that a rock formation could be identified by the fossils it contains. This deceptively simple concept enabled Smith to correlate the geologic age and position of rock formations in widely separated areas. Within a short time, geologists throughout the world had established chronologic sequences of time-rock units, called the *geologic column.*

The geologic column in a given region establishes a unifying time scale for the rocks within the Earth's crust. It consists of major and minor time divisions, arranged from the oldest rocks on the bottom to the youngest on the top. In this volume, the reader will be carried back to the beginning of the Earth in Precambrian time. This extremely long era includes more than three fourths of the Earth's history, lasting at least 3.5 billion years. Following the discussion of the Precambrian, the articles deal with the Paleozoic and Mesozoic eras.

Life in the geologic past constitutes the dominant theme of this volume. We begin our study by asking whether or not life existed in the Precambrian era. Except for some primitive life forms, very few fossils have been found in Precambrian rocks; however, the indirect evidence of the presence of life is strong. Early Paleozoic rocks (lying directly on the Precambrian rocks) exhibit fossils of rather highly evolved organisms. Therefore, we suspect a long evolutionary history in Precambrian time.

Subdivisions of the Paleozoic and Mesozoic eras have been derived from the names of areas where certain rock strata were first studied. For example, the oldest Paleozoic period is the Cambrian (from *Cambria,* the Latin name for Wales). The Ordovician, Silurian, Devonian, Carboniferous, and Permian constitute the remaining Paleozoic divisions. The Triassic, Jurassic, and Cretaceous periods are the main subdivisions of the Mesozoic era. The authors of this volume will lead the reader in chronological order through the geologic column, from Cambrian through Jurassic times. (The Cretaceous period will be covered in Volume 6, along with the entire Cenozoic era.) In each period, the dominant life-forms will be described and studied.

Invertebrate marine animals constitute the predominant element in the fossil record. Protista (one-celled organisms), Porifera (sponges), Coelenterata (including hydras, corals, and jellyfish), Bryozoa (tiny, colonial organisms that secreted their own skeletons), Mollusca (mollusks), Brachiopoda (diverse bivalve forms abundant in the Paleozoic era), Arthropoda (including the extinct trilobite), and Echinodermata (including starfish and sea urchins)—these comprise the animal phyla to be investigated.

Although not so abundant as the marine invertebrates, representatives of the phylum Chordata (fish, amphibians, reptiles, birds, and mammals) were important forms from the late Paleozoic to the present.

Finally, the Plant Kingdom is also represented in these pages.

ALBERT J. RUDMAN, Ph.D.
Associate Professor of Geophysics,
Indiana University

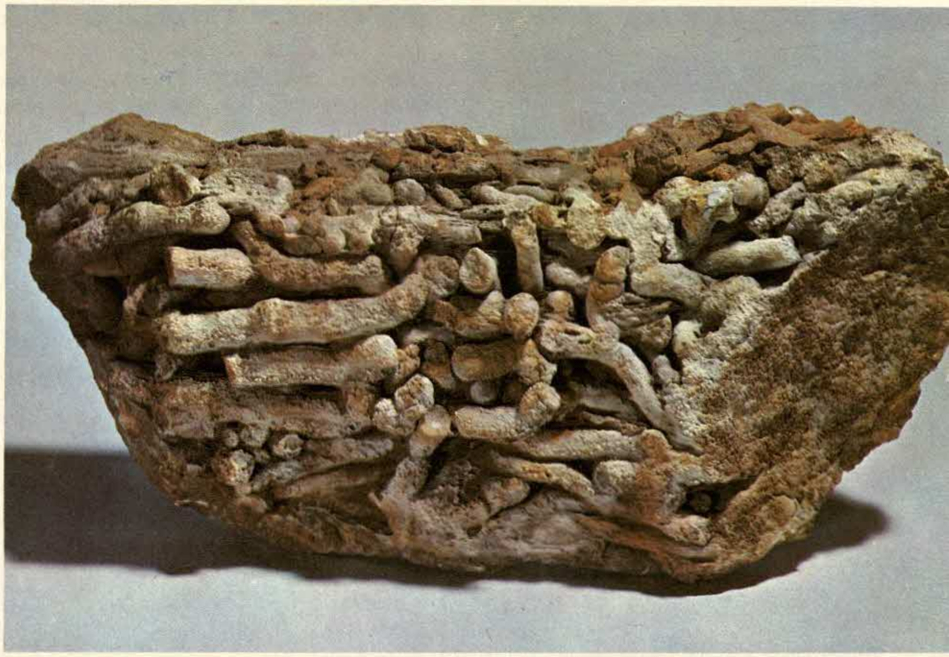
FOSSIL REMAINS | vital clues to evolution

The slow, progressive accumulation of sedimentary rocks has preserved innumerable remains and traces of living organisms, many species of which have long since vanished. These remains, which attest to the evolution of life on Earth, are called fossils. The study of fossils is far-reaching, for they provide vital clues to the geological and biological history of the Earth and to the principles on which the evolution of living organisms is based.

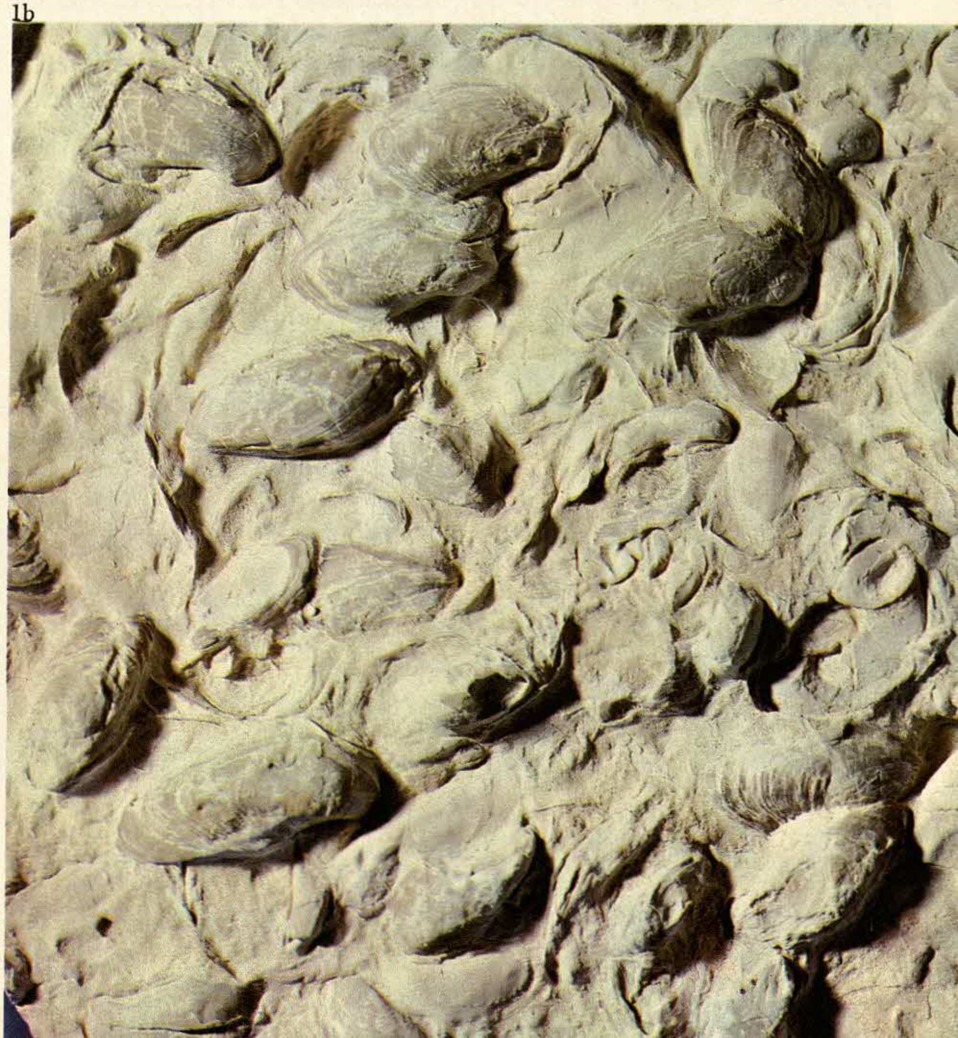
There are two distinctly separate kinds of fossils—those of plant origin and those of animal origin. Plant fossils are rare, and their study is not so significant to geology as that of the animal remains. The chief importance of plant fossils lies in the reconstruction of environments in which long-vanished life-forms once thrived.

It is difficult to pin down the term "fossil" precisely. At best, a fossil may be defined as the more or less mineralized remains of the body of a living organism often belonging to a species that is now extinct, and usually found enclosed in an ancient sedimentary rock. Some organisms living today, however, are species represented by fossils. The record of life on Earth for the past 600 million years is clearly written by an abundance of well-preserved organic remains.

1a

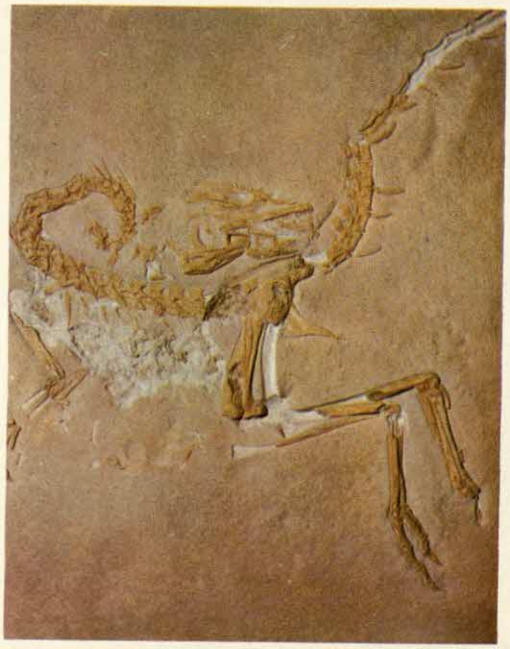


1b



FOSSIL ASSOCIATIONS—Special circumstances have sometimes resulted in the accumulation of large quantities of fossils, as these two photographs testify, with their numerous examples of Teredo, or shipworms (Illustration 1a) and Gervilleia (Illustration 1b). The accumulation of a large number of specimens of the same species may have occurred for different reasons. Understanding those reasons can help to inform the scientist about the life and behavior of these animals or about the process of sedimentation. Sometimes, in order to interpret a phenomenon correctly, it is necessary to study similar forms of present-day life. For example, accumulation can be produced by forms of colony life, as in the case of coral. It also can be produced by a collection of remains carried by water and piled up in a single place on the sea bottom where organisms lived or fell after their deaths. Illustrations 1a and 1b show special cases of large accumulations of fossils; the individuals of each colony are identical specimens. These specimens of Teredo and Gervilleia lived at least 130 million years ago.

2



A WELL-PRESERVED SKELETON—Fossilization of large organisms is always a more critical process than that of smaller life forms. More time is needed for a large animal to be buried and protected by sediments, and during this time it may be destroyed by other animals or by the force of moving water. Moreover, larger animals have always been less numerous than smaller animals. A well-preserved specimen like this fossilized portion of an animal that walked in an erect position, balancing itself on two hind legs and robust tail, is rare. When such a fossil fragment is found in a rocky stratum, painstaking search is made of the surrounding area in the hope of finding the entire skeleton. Often the remains of many similar animals are found in the same vicinity, and the exploration, sometimes lasting for months or years, may be extended to a much larger volume of rocks. Sometimes the process of fossilization has produced such a fragmentation of the remains of the animal that it is desirable to continue using the support given by the same rock that encased the fossil.

LIVING FOSSILS, MUMMIES, AND INCRUSTATIONS

The most recently formed petroleum deposits are never less than several million years old. Since that time, the organic materials from which this valuable product later was formed have been buried under marine sediments where they were permanently enclosed, isolated by the sealing rocks above them, and crushed at great depths by pressures measuring in tons per square centimeter. Nevertheless, some bacteria may have managed to survive from these remote epochs when the deposits first formed, imperturbably reproducing themselves within the mass of crude oil. They are extraordinary examples of living fossils. It would be difficult to find another accurate name for these organisms that have survived in the subterranean world of petroleum without light and air. (Some scientists believe these bacteria are recent organisms that were introduced into the crude oil during drilling.)

It also seems logical to describe as living fossils those species of animals and plants that, since earliest times, have undergone a practically imperceptible evolution and today still look identically like species that lived hundreds of millions of years ago. Specimens of Ginkgo, Metasequoia, Latimeria, Neotrigonia, and Lingula are living forms today that are identical to analogous fossils found in sediments with origins as far back as the Tertiary era. Thus these species also can be classified among living fossils, although with less justification than the petroleum bacteria. The bacteria, therefore, may be considered the highest degree of preservation of a fossil species.

Mummification is a lower degree of preservation of a living organism. There are many ways in which the remains of an organism can be preserved by mummification. The highest form of this type of preservation is that produced by deep freezing. From time to time the ice of Alaska and Siberia frees perfectly preserved bodies of mammoths, or Ice Age elephants, which disappeared from those regions at least ten thousand years ago. Mummification also can be produced by the rapid sealing of a dead organism in a material which can keep out atmospheric oxygen and thus block the proliferation of decomposing microorganisms. At Starunia in the Carpathians are rocks made up of large amounts of asphalt, which covered over and perfectly mummified the remains of innumerable organisms. Other examples are the processes of cadaver mummification employed by ancient Egyptians; these processes were based on the abundant use of unguents, the effect of which was similar to that of natural asphalt.

A mummifying effect also occurs on tiny organisms that are enclosed in silica immediately following their deaths, or that die by being trapped in silica that has been rapidly precipitated from hot spring water. Incrustation on the part of minerals that deposit rapidly, like travertine limestone, which quickly precipitates from hot spring waters, can also produce the fossilization of an organism. However, it is quite difficult to extract fossils produced in this manner, in order to reconstruct them in their primitive form.

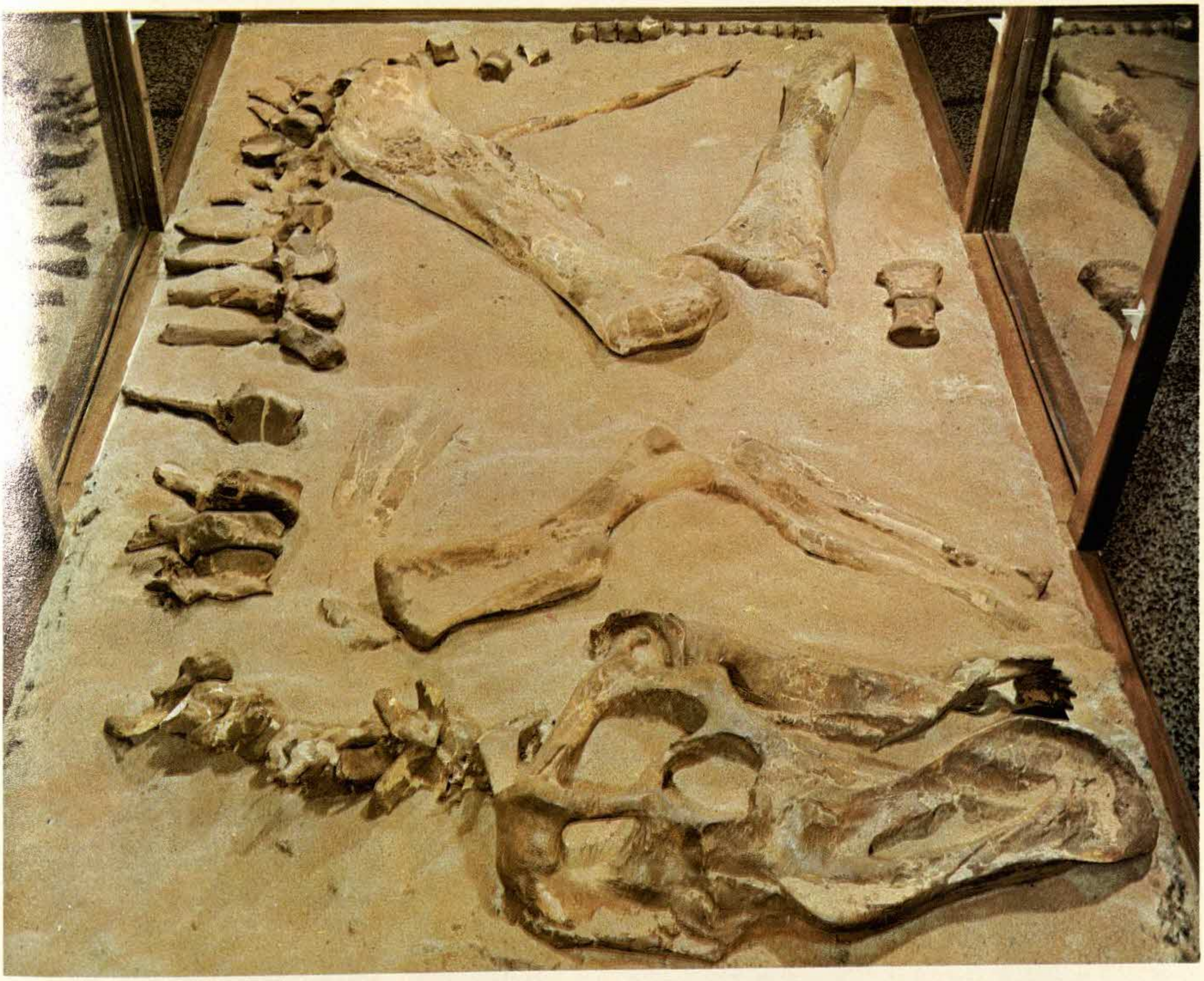
FOSSIL STUDY

Paleontology, the study of fossils, has applications in the fields of ecology, zoology, and botany. The fields of interest of most paleontologists fall into categories concerned mainly with geology or biology. The study of rock strata made great strides after the discovery that each rock bed contains characteristic fossils and that beds in vertical succession show sequences of characteristic fossils from base to top. Because fossils occur widely and because many museums have outstanding collections, amateur paleontology is a rewarding pastime.

MICROPALEONTOLOGY

The study of microscopic fossils is a division of paleontology. It differs in the size of the specimens, the methods of preparing and studying them, and in the extensive use to which micropaleontology is put in stratigraphy and petroleum geology. Some microfossils belong to groups whose members are typically small, and others are fragments of larger plants or animals. In this category are fossil spores and pollen; embryonic shells of mollusks; scales, teeth, and earbones of small fish; and skeletal plates of sea cucumbers. Microfossils are collected by the hundreds or thousands in rock samples. Sometimes the sample may be reduced to fine particles, in which case the microfossils are picked out of the debris. Sometimes the microfossils are floated out with a liquid having a specific gravity that will cause it to lift them but not the matrix. A wide-field stereoscopic microscope that can magnify the specimens from 10 times to 100 times is used in the study of most microfossils.

AN ANCIENT AND WELL-PRESERVED FOSSIL.—This dinosaur fossil is better preserved than the one in Illustration 2, even though this one is older. Nevertheless, this fossil also has been left in its mother rock, with the purpose of showing how it lay at the time it was discovered. Because many of its pieces have been lost, it could not be reconstructed in an erect position. 3



HOW FOSSILS ARE FORMED

the preservation of organic remains

The existence of an abundant and diversified array of fossils enables geologists not only to learn about the organisms that lived long ago, but also to reconstruct the geological conditions that existed during the times when the fossils were formed. Normally, the death of a living organism is followed by its total destruction; therefore, the abundance of fossils found in ancient rocks bears testimony to the profusion of life-forms that populated the Earth during the various geological eras.

PRESERVATION–THE EXCEPTIONAL CASE

Ordinarily, when an animal dies, its remains are quickly destroyed. Frequently, death occurs because the animal is hunted down and killed for food; then its remains disappear rapidly without leaving any traces. Such is, and always has been, the way of the animal world both on dry land and in the sea.

Even in cases where death can be attributed to accidental or natural causes, the remains usually are devastated by scavengers and decomposed by microorganisms. Only in special cases are the corpses buried by sand or other material that gives them a chance of being preserved. Circumstances in aquatic environs are more favorable to the preservation of the dead organism than are conditions on land. Dead animals (excluding those devoured by their enemies) sink to the bottom of the sea or other water body, where their soft organic substances are destroyed by decomposition, while more resistant parts, such as shells or skeletons, remain. Real preservation occurs if the organisms are covered with silt, which protects the remains against microorganisms and other agents of destruction. At this point mineralization begins, the end result of which is the transformation of organic substances into mineral substances. Chemical reactions occur successively, and the substances formed by the decomposing organisms are gradually replaced by other materials that permeate the slowly hardening sediment surrounding them.

How long does this process take? Pliocene shells deposited from two to 10 million years ago are still found today; these shells are the same ones that are renowned for the beauty of their mother-of-pearl. Therefore, the replacement of organic substances by minerals may take about 10 million years. This length of time is inconsequential in comparison with the time that has elapsed since the first sedimentary rocks, containing the most ancient fossils, formed over a billion years ago.

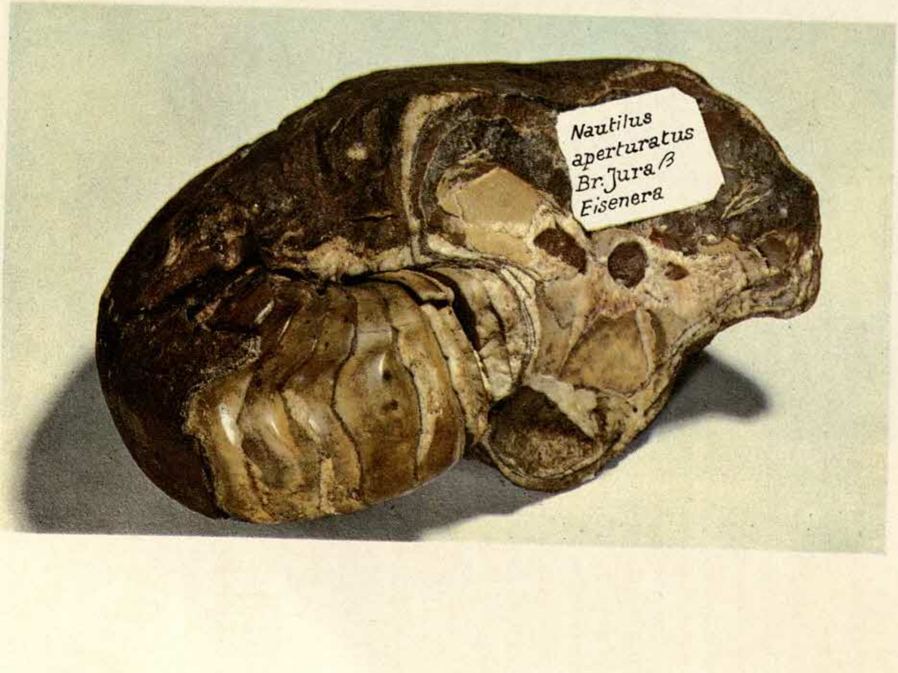
Fossils that are hundreds of millions

HOW FOSSILIZATION OCCURS—Fossilization may occur in different ways. Some fossils are simply the imprints, tracks, or trails left by animals in soft mud or other sediments that subsequently hardened. Other fossils consist of the unaltered hard parts of animals (such as shells, bones, and teeth) that have been protected against decay by a covering of sediments. In rare instances, entire organisms have been preserved. In Siberia, for example, scientists have discovered woolly mammoths frozen in ice; this kind of fossilization has resulted in the almost perfect preservation of the skins, flesh, and soft, internal organs, as well as the skeletons and other hard parts.

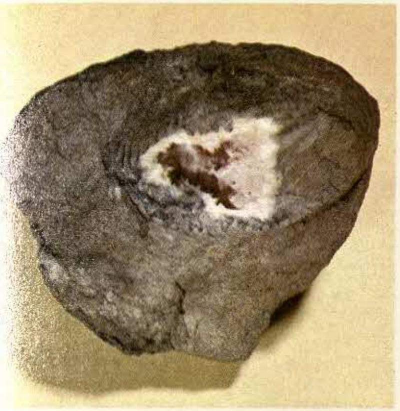
Most fossils, however, are changed in some ways. Water may dissolve and remove some of the material of the hard parts. Commonly, a chemical substitution or replacement occurs; when this happens, the original materials comprising the hard parts are replaced, particle by particle, with some mineral contained in the water, such as calcium carbonate, silica, or iron pyrite. Sometimes, when the hard parts of an animal have been covered with sediments, the original material is carried off in solution, leaving a mold or impression of its form in the enclosing rock. This cavity may be filled with another mineral substance, which hardens to form a cast of the animal form. In other words, a cast may be formed from a mold.

The fossil shown in the illustration was discovered in a layer of rocks formed about 150 million years ago. It is *Nautilus aperturatus*, a common fossil from the Jurassic period. While it was being extracted from the enclosing rock, it was partially chipped, revealing the process of fossilization. Early in the process the animal was filled with a light-colored carbonate that fortified it and prevented it from shattering under the pressure of overlying strata. At the same time, the surrounding rock closed around it so tightly that the specimen became as smooth as the rock itself. Some time later, the water circulating inside it eroded the shell, which was then replaced by the minerals present in the water. Finally, part of the enclosing sediment, which was really a cast of the fossil, was replaced by pyrite. This replacement occurred in layers along concentric surfaces.

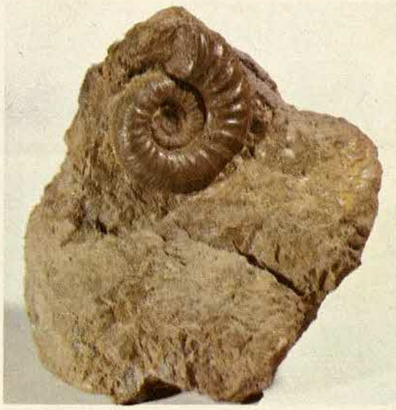
1



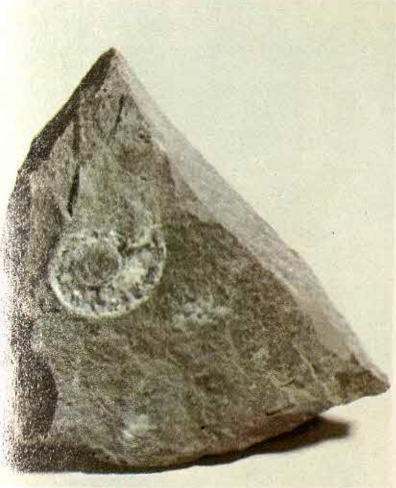
2a



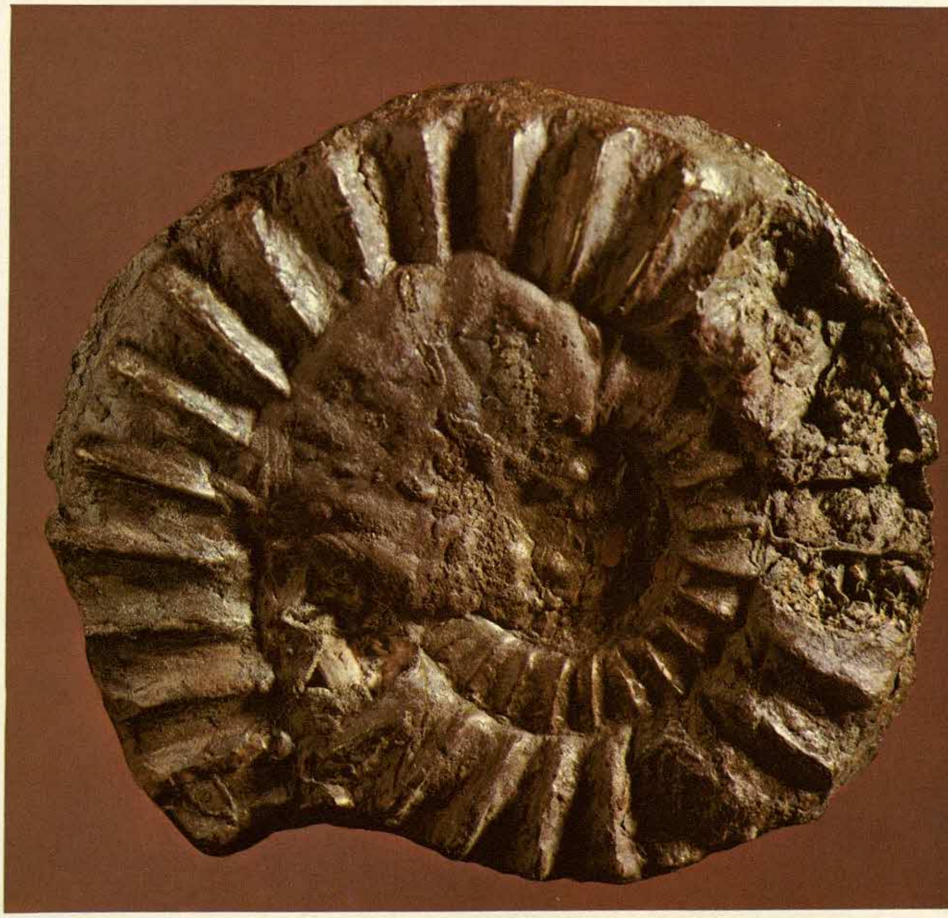
2c



2b



2d



DIFFERENT TYPES OF REPLACEMENT MATERIALS—A large variety of minerals may replace the original organic matter during the process of fossilization.

The inside of *Macrocephalites* (Illustration 2a), from the Jurassic period, was replaced by celestite and calcite. Celestite is strontium sulfate ($SrSO_4$) and calcite is calcium carbonate ($CaCO_3$), one of the most common minerals dissolved in water. The center of the cavity was partially filled, and the crystals that were formed by the deposit spread toward the inside of the remaining cavity.

The *Arietites* shell (Illustration 2b), of the Triassic period, was partially replaced by quartz and calcite. The calcite was deposited more quickly than the quartz, which formed almost invisible crystals. The rhombohedral crystals of calcite are clearly visible.

The *Perisphinctes* shell (Illustration 2c) was replaced by ferric hydroxide, which gives the fossil its reddish-brown color. The rock containing the fossil is a common limestone.

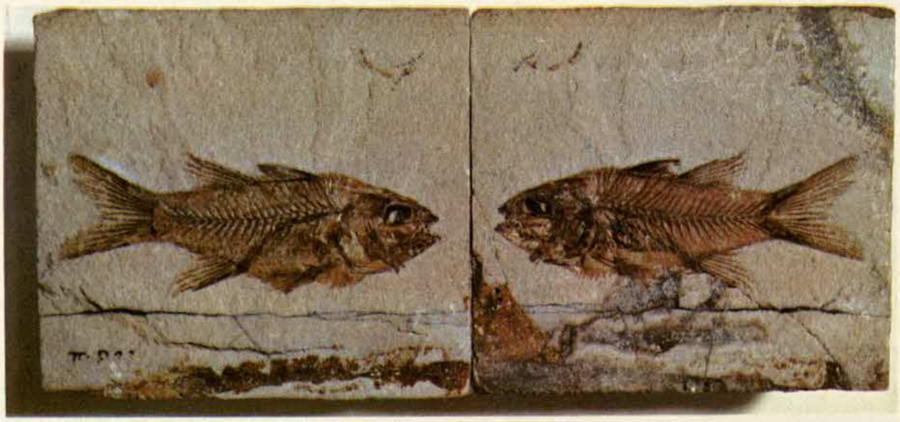
The ammonite shell (Illustration 2d) was replaced chiefly by pyrite. In this case the pyrite formed minute crystals inside the fossil. In some cases pyrite has replaced and completely filled the original shell, giving the fossil a somewhat metallic appearance.

---

of years old have lost most of their original characteristics, but some of their original organic material may still be found in the minerals.

Factors involved in determining the validity of the fossil record of ancient life include the nature of organisms, their geographic and ecological distribution, the types of rocks, sites of deposition, and geological time. The degree to which organisms are subject to preservation varies highly. In general, the deposits formed along sea margins, either on land or in relatively shallow marine waters of continental shelves and broad epicontinental seas, are the most likely to be preserved and later made available for study. Erosive forces tend to be at a minimum in such regions. Records of early organisms that lived in higher continental interiors or in open seas are rare. Only since the late Mesozoic era have upland continental deposits been well preserved.

3

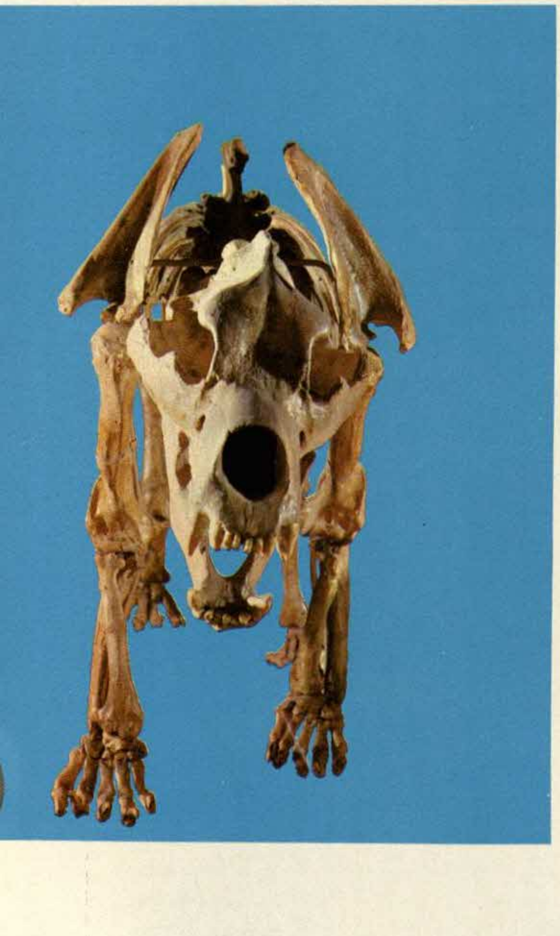


A 70-MILLION-YEAR-OLD FISH—Some 70 million years ago, a great sea lay where the Alps stand today. In this sea lived great numbers of fish, most of which resembled modern-day fish.

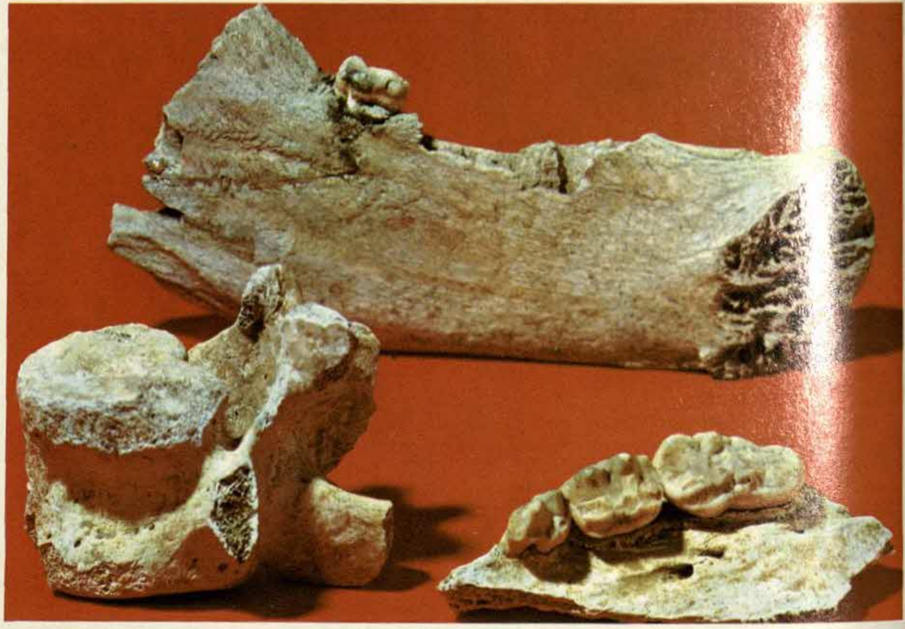
This photograph shows a fossil of *Labrax lepidotus* preserved in the rocks of Monte Bolca near Verona, Italy. It is an especially interesting example of fossilization, because it clearly reveals details of anatomy. When the fish died, it sank to the bottom, where it was quickly covered by slime. Its organic substance then decomposed, but not all the decomposed matter was carried away. Consequently, in the successive process of replacement a part of the residue (including a tiny amount of carbon) remained, coloring the minerals.

The rock in which the fossilization occurred was opened by a blow struck along its parallel planes according to the line of least resistance. The person who sensed the presence of the fossil in the block of rock carefully broke it open with wedges inserted into the plane holding the fossil. The fossil split into two parts that remained fixed to the faces of the rock, showing two spectacularly identical imprints that are extremely clear and detailed.

4a



4b

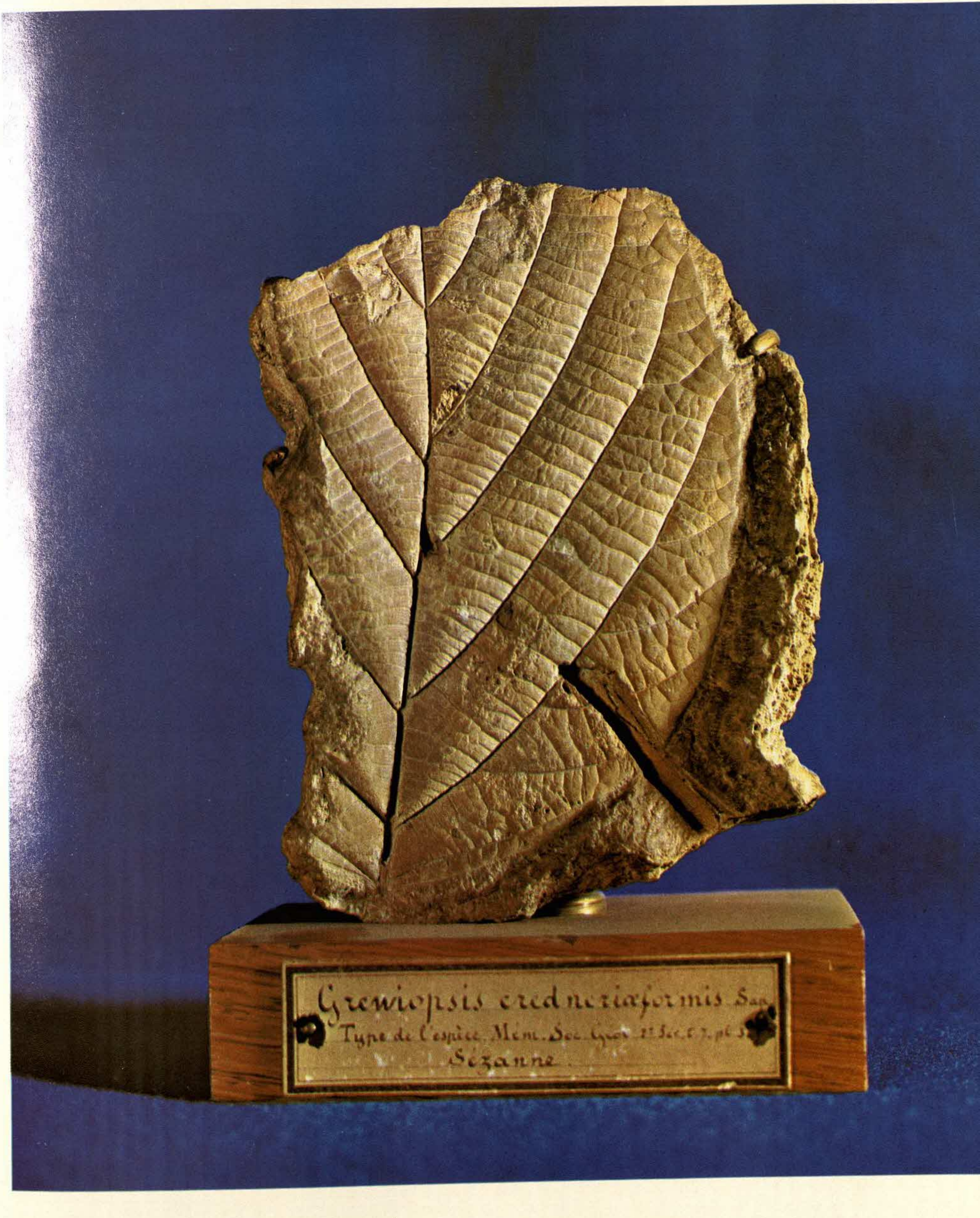


RECENT FOSSILS—These illustrations show the fossilized bones of the cave bear, *Ursus spelaeus*, which lived until a few tens of thousands of years ago in caves all over northern Italy. The complete skeleton of the cave bear (Illustration 4a) was found in the Pocola grottoes near Trieste. The process of fossilization has neither destroyed the delicate nails nor replaced the materials comprising the bones.

The mandible, vertebra, and teeth of the cave bear (Illustration 4b) were recovered from the San Giovanni Llarione grottoes near Verona. These remains prove that neither the process of replacement nor the consolidation of sediments in which these specimens were found had yet begun. The remains were extremely fragile; before they could be handled, they had to be filled with reinforcing substances.

In comparison with the fossils illustrated on the two preceding pages, the cave bear fossils are very recent.

PLANT FOSSILS | their formation and significance


Grewiopsis credneriaeformis Sap.
Type de l'espèce, Mém. Soc. Géol. 2e Sér. t. 7, pl. 3
Sézanne.

← **A HIGHLY DELICATE STRUCTURE PERFECTLY PRESERVED**—The complicated vein structure of this *Grewiopsis credneriaformis* leaf (Illustration 1) has been perfectly preserved for millions of years, locked in a sediment that consolidated to form a rock. The fossil was brought to light through the use of a geologist's hammer.

This fossil is a magnificent example of a cast. The original material of the leaf was carried away by water that helped form a mold for the cast. Perhaps the leaf itself was carried for quite a long time before sediments formed the cast. The minute details were preserved for the most part by the fine texture of the enclosing sediment. Although this kind of fossil is not uncommon, paleontologists have difficulty splitting the encasing rock in such a way as to separate the two parts of the cast perfectly. Often one or both parts are broken.

In the discussion of fossils and the process of fossilization, no mention was made of plant fossils. These remnants of the past, however, play a special role in the paleontological history of the Earth.

The total mass of living plant matter, both on land and in the seas, has always been greater than that of animal matter. Today, as in the past, plants dominate the Earth, at least quantitatively. Therefore, one might assume that plant fossils are abundant in rocks. Such is not the case. Plants lack skeletons that are resistant to decomposition; therefore, relatively few plants have been preserved. Exceptions exist, of course: coal testifies to the conservation of carbonic matter from great masses of plants. However, not all coal formations reveal traces of the original matter. Scientists experience difficulty in determining whether or not a piece of coal is actually a plant fossil, and in determining which kind of plant was the source of the matter in the coal.

In other cases, different processes have led to the conservation of plant fossils. The discovery of a plant fossil is of special importance because it is a rare event and because it broadens man's knowledge about the environment in which the fossil was formed. Such a find can even lead to a reconstruction of the landscape in which the plant originally grew.

THE MEANING OF PLANT FOSSILS

In the history of life on the Earth, animals have undergone an extremely rapid evolution. Therefore, their fossils have great importance as geological chronometers. Certain species were so short-lived that their fossils have been dated with a relatively high degree of accuracy. By geological standards, an error of a few million years is of minor significance.

Plants, on the other hand, evolved very slowly. Therefore, the ages of plant fossils cannot be determined with the same degree of accuracy as can the ages of animal fossils. Certain plant species present today have existed for tens or hundreds of millions of years; they are, in effect, living fossils. Specimens that lived ten, 50, and 100 million years ago would exhibit scarcely any morphological differences that could be used to determine age differences. Consequently, plant fossils are of little or no use in terms of dating.

Plant fossils provide more information about climates than do animal fossils. Although certain animals lived only in cold climates and others lived only in warm climates, exceptions have always existed. Sometimes the same species lived in different climatic regions during different eras. Mammals have lived in both hot and cold climates; their bodies have been distinguished by outward modifications, such as fur, that are not evident in most fossils. Today elephants live in tropical climates, but not more than 20,000 years ago their ancestors (the woolly mammoths) thrived in glacial climates. Consequently, animal fossils do not serve as precise indicators of climate.

2

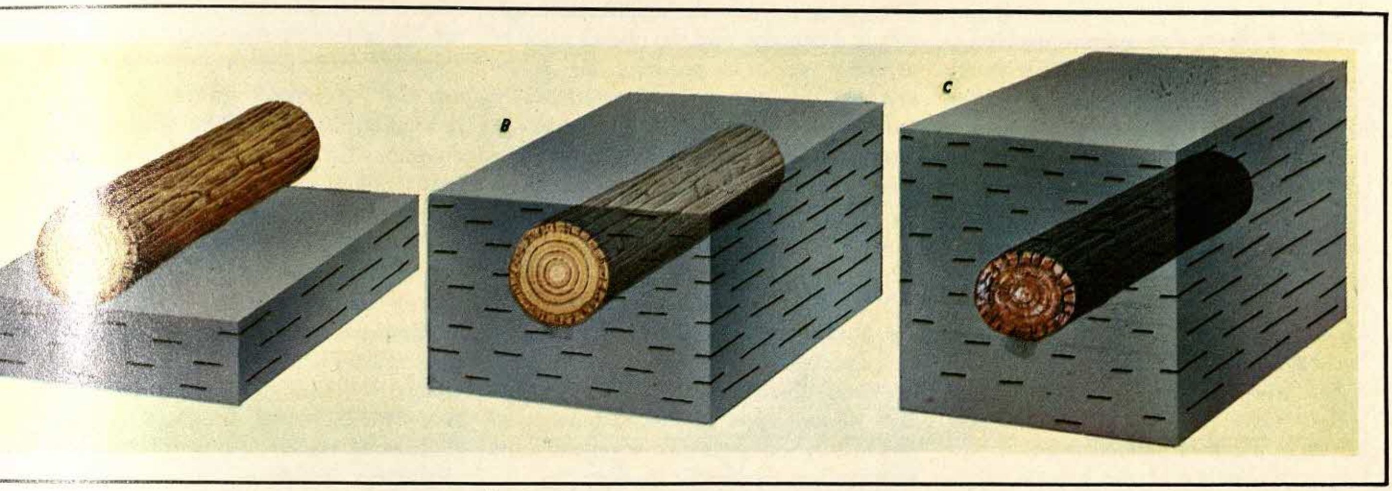
THE MECHANICS OF FOSSILIZATION—When a plant dies it falls over on the ground (a). If the plant is a tree with leaves and a trunk, the leaves are preserved only if they are immediately covered with sediment. The trunk may resist decomposition for a long time, especially in an arid climate where decay processes are slow.

Usually, the only part of the leaves that is preserved is the ribbing, while the organic substances of the trunk—especially the carbon that separates slowly from the cellulose—are conserved. In the meantime (b), the weight of the overlying sediment crushes the trunk, which may maintain its form. If the trunk undergoes partial decomposition before the sediment hardens, it may be reduced in size by as much as one eighth.

At a later date (c), the total or partial replacement of organic substances may occur.

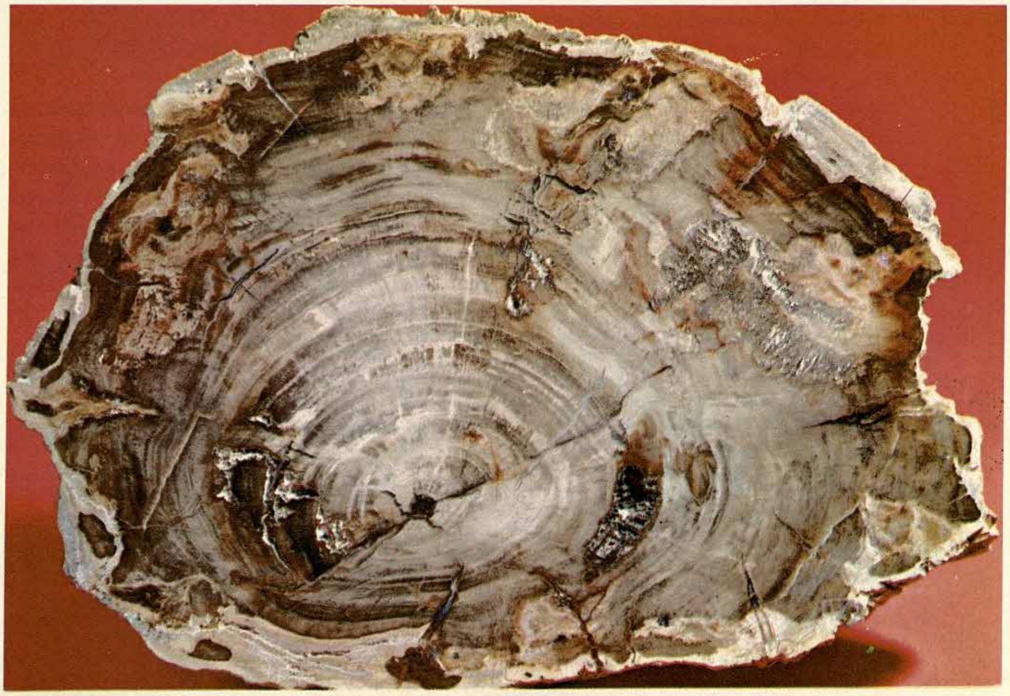
3

In contrast, a plant fossil is almost always a good climate indicator, especially if it is a plant form that still exists today. The conifers have always grown in temperate or cold climates, while palms have always grown in hot regions. The discovery of palm fossils in Arctic regions and conifers in tropical or subtropical areas is a sure indication that a change in climate has taken place since these plants died. Pollen fossils are also often found in sedimentary rocks. Pollen



← **A 70-MILLION-YEAR-OLD PLANT**—This plant (Illustration 3) lived some 70 million years ago. The fossil is extremely well preserved. The stem consists chiefly of carbon, the major constituent of cellulose. The leaves have only partially conserved their organic substances. In the places where some leaves have folded over others the characteristics of the bottom leaves show through the transparent upper ones. Scientists find it extremely difficult to bring to light such a large plant fossil as this. The recovery of such a fossil requires as much time and effort as the restoration of a work of art.

4



A SILICIZED TRUNK—In the preceding figure the petrifying substance was calcareous; in this trunk (Illustration 4) it was siliceous. The trunk was covered with sediments before decomposing, and its shape has been perfectly preserved. Then water rich in silica penetrated the trunk, carried away the organic material, and replaced it with silica. At first the water penetrated through the crevices in the wood; then it dissolved the rest of the trunk. Gradually, as the replacement continued, the composition of the water changed; it became contaminated by parts of the materials dissolving from the trunk. Some rings completely disappeared because of the speed of replacement. Quartz crystals can be found in their place.

grains are easily recognized under a microscope, and through a study of these grains, paleontologists can reconstruct the flora of long-passed epochs.

Rapid burial in fine-grained sediments or volcanic ash aids the formation of impressions of leaves, seeds, and an occasional flower. Circulation of ground water (carrying minerals in solution) may result in the substitution of those minerals for the organic materials of the plant tissues, thus preserving details of cell structure.

Deeply buried plants may be subjected to pressure and heat until their volatile constituents are distilled away, leaving a film of carbon, in the case of leaves, or carbonized logs, in the case of stems. In very rare circumstances, where bacterial action is inhibited, the details of the plants are retained as molds.

THE HISTORY OF EVOLUTIONARY THEORY

from Linnaeus to Darwin

The best way to understand how existing species of plants and animals evolved is by studying paleontology—a fairly young science based on the accurate estimation of the ages of fossil species. Fossils are the remains or other evidence of the physical features of the life of the past; they are preserved in association with rock strata. Fossils associated with the older of two identifiable strata are obviously the fossils of life-forms that existed at an earlier date. This kind of correlation has been known for some time, but it has failed to provide two other important types of information: how long ago these plants or animals lived, or how long any member of the species represented by the fossil may have lived. Yet without the answers to such questions, there can be no study of evolution. Modern paleontology helps provide these answers.

The first conclusion to be drawn from the history of paleontology was that living species are not always the same and, what is even more important, they have not always been the same. This conclusion, revealed by observing successions of fossils, long troubled scientists; only recently have complete and satisfying explanations been offered as a result of a succession of stages leading to current knowledge of the evolution of species. These stages were: the definition of species as a concept, and the classification of as many species as possible; the discovery that the inherited characteristics of individuals of the same species may vary (mutate), and the study of how and why these variations occur; the discovery of the laws of heredity; the discovery and study of the role of natural selection in the evolution of species.

Most of these discoveries resulted from the study of existing species, but the study of the fossils of extinct species discloses in greater detail the history and laws of evolution. A brief summary of this history indicates how scientists came to formulate the theory itself.

THE FIRST STEP: THE IMMUTABILITY OF SPECIES

The concept of evolution was formulated in ancient times, but merely as a philosophical term, with none of the connotations currently understood. The concept was first applied in a scientific sense in the eighteenth century, when the first attempts were made to collect and classify species of plants and animals. In 1758 the Swedish naturalist, Carolus Linnaeus, published his masterpiece, *Systema Naturae,* in which he classified all the living species known in his time.

LINNAEAN CLASSIFICATION

								CLASS
STAMENS AND PISTILS	visible (*Phanerogamia*)	occurring in the same flower	stamens not joined to pistils	stamens not joined	stamens uniform	1	in each flower	1. Monandria
						2	" " "	2. Diandria
						3	" " "	3. Triandria
						4	" " "	4. Tetrandria
						5	" " "	5. Pentandria
						6	" " "	6. Hexandria
						7	" " "	7. Heptandria
						8	" " "	8. Octandria
						9	" " "	9. Enneandria
						10	" " "	10. Decandria
						from 11 to 19	in each flower	11. Dodecandria
						20 or more	perigynous	12. Icosandria
							hypogynous	13. Polyandria
					stamens irregular	4, of which 2 are longer		14. Didynamia
						6, of which 4 are longer		15. Tetradynamia
				stamens joined	filaments in one bundle			16. Monadelphia
					filaments in two bundles			17. Diadelphia
					filaments in several bundles			18. Polyadelphia
					with united anthers			19. Syngenesia
			stamens joined to the pistil					20. Gynandria
		not occurring in the same flower	plants monoecious					21. Monoecia
			plants dioecious					22. Dioecia
			plants polygamous					23. Polygamia
	invisible (*Cryptogamia*)							24. Cryptogamia

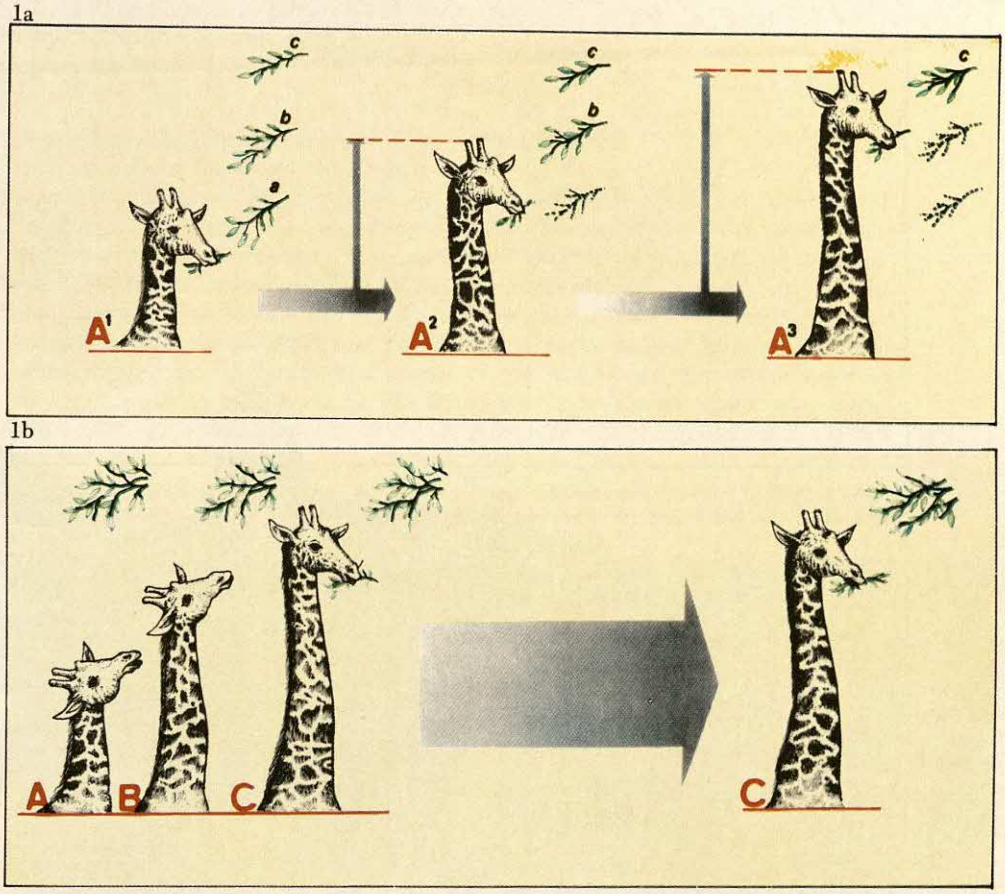
Linnaeus himself believed in the immutability of species, that is, that the species he listed had characteristics that were retained generation after generation, throughout the centuries. However, his enormous list of plants and animals was in itself a great contribution, although it did not actually lead to the theory of evolution of life-forms, that theory could not have developed without the organization of some classification such as that of Linnaeus, who made the development of evolutionary theory possible. The Comte de Buffon, a naturalist contemporary with Linnaeus, disagreed with him, postulating that all living species gradually came to differ among themselves, which suggested they all derived from some common origin. Buffon was not an evolutionist because he did not believe that the original type was simple and had "evolved" into a variety of more complex types; on the other hand, his notion was that the existing species were the results of a degeneration of more perfect species—for example, that the donkey was a degenerate species of horse.

LAMARCK: A HINT OF EVOLUTION

The Chevalier de Lamarck, a French naturalist who lived about fifty years after Linnaeus, hinted at the possibility that living species might not be immutable but might have evolved from earlier forms, in the sense that they acquired increasing complexity. Lamarck tended to attribute this complexity to an environmental process—each learned from its environment and passed on the new information to the next generation. This study of the relationship between species and environment became, in fact, the next step in the direction of the modern theory of evolution.

According to Linnaeus, for example, a polar bear, because it has white fur, differs from all other bears and must be placed in a class by itself. However, other naturalists began to ask why polar bears have white fur; they concluded that such fur is more suitable than dark fur to the surroundings in which the polar bear lives. Lamarck believed that the environment made it necessary for the bear to change the color of its fur, and indeed caused the bear to do so. The flaw in this reasoning was that it failed to demonstrate how the whiteness of fur became an inherited characteristic of polar bears. The missing clue would appear with the development of the science of genetics, but in Lamarck's time the discoveries of Gregor Johann Mendel were not yet available.

Nevertheless, Lamarck's work was not in vain. It presented the concept of the adaptation of species to environment, and stressed the possibility that a relationship exists between the forms and characteristic functions of each species and the environment in which it flourishes.



THE THEORIES OF LAMARCK AND DARWIN—According to Lamarck, environmental conditions determine changes in the structure of an organism. The giraffe, for example, has a long neck because it has to stretch to higher and higher branches in search of food (Illustration 1a). As generation succeeded generation, this characteristic became more pronounced until it took its present form.

According to Darwin, evolution takes place through a process of natural selection that operates by favoring the survival of the best-adapted individuals (Illustration 1b). Thus a long-necked giraffe has an advantage over a short-necked giraffe in the amount of food it is able to find; as a result, more long-necked giraffes will survive and pass on to succeeding generations the characteristic that made their success possible—a longer neck.

CUVIER: THE THEORY OF CATASTROPHISM

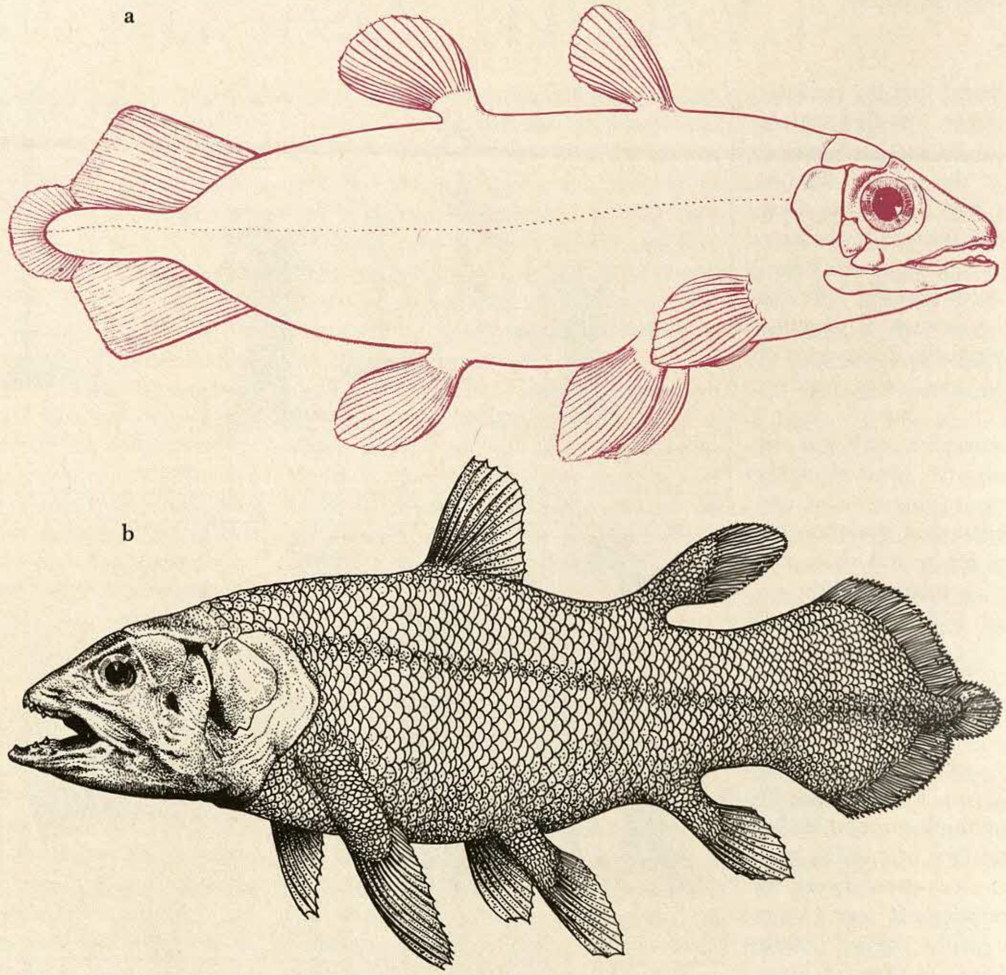
Lamarck's theory was demolished by Baron Georges Cuvier, a French anatomist who, in attempting to support his belief in the immutability of species, nevertheless helped lay the groundwork for the theory of evolution. It was Cuvier who first systematically studied fossils, comparing their forms to those of living species. Inasmuch as most fossil remains are fragmentary, it is difficult to reconstruct any semblance of a complete species as it existed when it flourished, and this task was far more difficult in Cuvier's day. Cuvier introduced the method of applying analogy in this field; he compared the structures of completely extinct species with corresponding parts of living species, and suggested that similar structures may imply similar functions. Cuvier was the first to concentrate on the innumerable kinds of fossils abounding in the rock strata and the first to interest scientists in studying them. He also tried to account for the origin of these remains by postulating that when the Earth first developed, the number of species was even greater than at present, and that with the passage of time most species became extinct and only a small fraction survived. He further tried to attribute the disappearance of so many species to natural catastrophes such as floods, volcanic eruptions, earthquakes, the submerging of landmasses by the sea, and climatic changes that were too sudden to permit migration. Cuvier did not originate this theory, known as catastrophism, but he adopted it as a reasonable corollary to his own concept of the diminution of the number of species. Some of the proponents of catastrophism went so far as to assert that, since the beginning of time, 27 such catastrophes could be identified.

So it was that Cuvier's work, although opposed to the theory of evolution, nevertheless indirectly clarified the concept of species and encouraged an anatomical approach to the study of the characteristics of species. After Cuvier, only a few more observations were needed to establish the laws of evolution.

TURTLES, FINCHES, AND LIZARDS: EVIDENCE OF EVOLUTION

In 1831 the English sailing ship H.M.S. *Beagle* began a circumnavigation of the

2



A PERFECT RECONSTRUCTION—Cuvier prepared the ground for the theory of evolution, because he greatly developed the science of paleontology. On the basis of his theories, and using a few fossils, paleontologists reconstructed the *Undina* (Illustration 2a), which is thought to have flourished in the Cretaceous period. When the *Latimeria* (Illustration 2b), a living genus, was discovered, it was realized that this fish (the coelacanth) was very similar to the *Undina*, and the accuracy of the reconstruction of the extinct genus was confirmed.

world; on board, as the ship's naturalist, was a young man, Charles Darwin. No journey ever yielded more to science, for the voyage afforded Darwin the experiences that he used to construct his theory of the evolution of species. During the voyage the ship stopped at the Galápagos Islands, located on the equator in the Pacific Ocean about 1,000 km (about 650 mi) west of the coast of Ecuador. These islands have a tropical climate and fauna substantially different from that of the distant mainland; the main differences involved special adaptations of the island species to their environment. For example, Darwin observed 13 species of chaffinch, each of which had differently adapted the structure of its beak or claws to enable it to capture prey. He saw similar adaptations among other species, especially among lizards and turtles. It was inconceivable to Darwin that when life began on Earth, existing species were particularly adapted to the environment of these islands; on the other hand, they must have reached those islands as the result of some catastrophe, and there begun the process of adaptation.

By Darwin's day the groundwork for the theory of evolution had been prepared. Darwin himself had observed how morphological characteristics varied within the same species that had lived for generations in the same place. He also knew that, when a species is spread over a vast area, variations are more marked among individuals living on the fringe of the area—even to the extent that such individuals can no longer mate, and thus constitute in effect two species.

Although Darwin did not yet know the reasons for evolution, he was able to demonstrate that evolution is responsible for variations of species. He had refuted the theory of the immutability of species, and evidence supporting the theory of evolution continued to amass. Darwin's contribution consisted of postulating that species evolved as a consequence of a process of natural selection, and that this selection was based on the survival of those species that were best able to adapt themselves to their environment.

ADAPTATION AND SELECTION

the mechanics of evolution

Geologists estimate that the Earth is about 4.5 billion years old and that living things have existed on it for at least the past billion years. The first organisms to appear were very simple ones, probably no larger nor more complex than the single-celled bacteria that exist today. It is now believed that these organisms developed in ocean waters, probably along the shoreline. Here they had all the water and minerals that they needed, and they were well adapted to living in this environment.

The world is not all ocean shorelines, however. There are ocean deeps, fresh-water lakes and streams, cold mountaintops, and dry, rocky areas. The first organisms and their descendants must have been carried by waves and winds into these environments, where most of them could not survive because it was too hot or too cold, too dark or too bright, or too deficient in food, minerals, or oxygen. Occasionally, however, some organism a little different from the others would be able to survive and reproduce. If the ability to live in the new environment was inherited by the organism's descendants, they, too, would live and produce still more offspring in this new habitat.

The idea that new species could arise from older species was not readily accepted by scientists before 1859. Prior to that time it was assumed that species were immutable, or unchangeable. It was believed that all the species of plants and animals existing then were created at the same time and that no new species could ever arise. In 1859 Charles Darwin published his famous book *On the Origin of Species by Means of Natural Selection.* He suggested in it that new species could arise from pre-existing species by adaptation to new environments. Darwin's theory slowly gained approval and is generally accepted today.

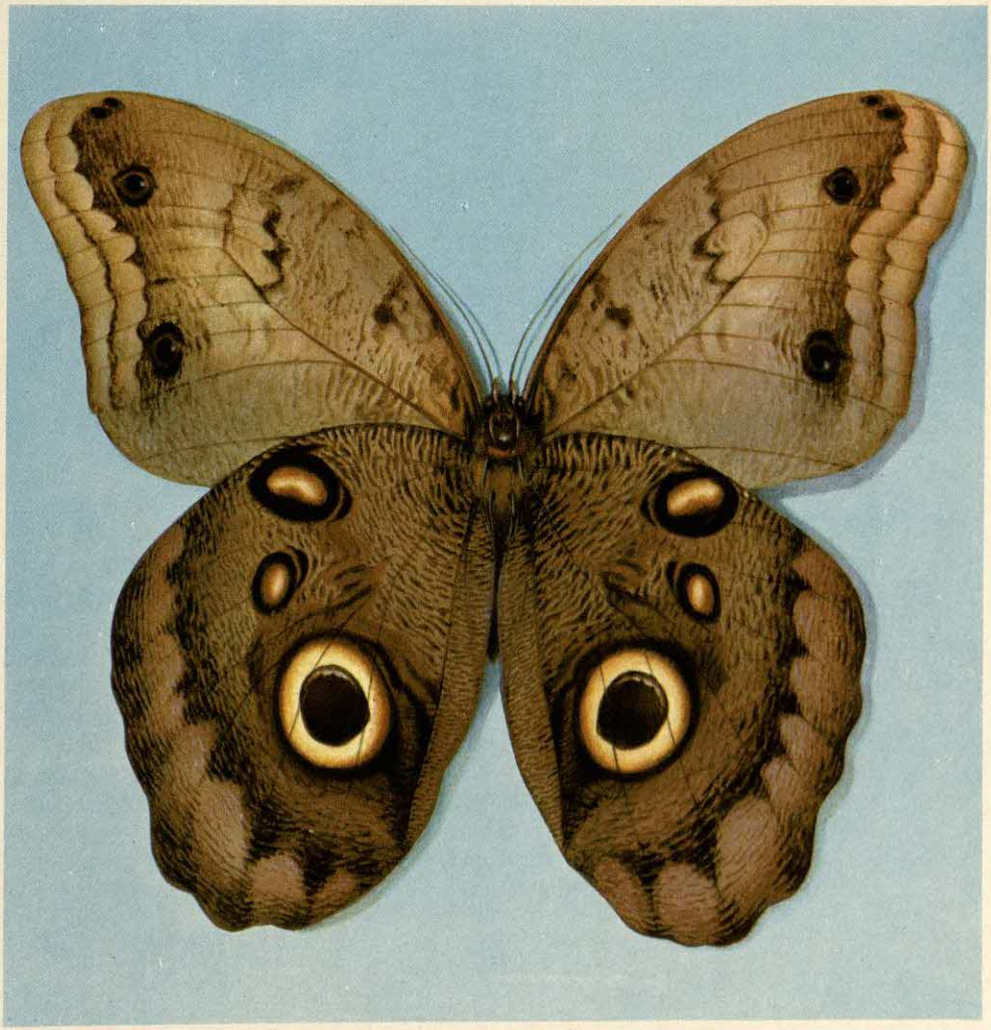
The environment of an organism includes not only its physical environment but also the plants and animals around it. In addition, the physical and biological environments of the world have not always been the same. The Earth has undergone periods of great climatic change, and new species of organisms have appeared. Older species had to adapt to the new conditions or become extinct. The adaptations that fit an animal or plant to its environment are the result of natural selection acting upon heritable variation.

ADAPTATION

The cacti of the American deserts and the euphorbias of the African deserts are good examples of plants adapted to living in extremely dry environments. They have thick, fleshy, water-storing stems that conserve water. The compact shape of the plants decreases the amount of surface area through which water might evaporate, and the epidermis is covered

PROTECTIVE COLORATION—The wings of the owl butterfly, *Caligo prometheus*, have large spots the shape and color of owls' eyes. These markings are believed to frighten away insect-eating birds that would otherwise prey on the butterfly.

1



with a waxy cuticle that also reduces water loss. Many of these cacti have very light green, almost white, coloration that reflects the sun's rays and prevents the plants from heating up and drying out. Grazing animals that might otherwise use these plants as a source of food or water are often discouraged by the sharp protective spines on the stems.

Butterflies and moths, many of which are sought after by birds, have evolved several different types of coloration that protect them from their enemies. Some butterflies have brilliant patterns that are assumed to startle and frighten their predators. The owl butterfly, for example, has designs on its wings that look like an owl's eyes; this may frighten away a species of butterfly-eating bird that is preyed on by owls. This type of adaptation is of value only to butterflies living in areas where owls eat birds that eat butterflies; in an area without owls, birds would not be frightened by anything resembling an owl.

One of the most general of all adaptations involving color is the gradation from darker coloring on the dorsal surface to paler coloring on the underside of animals. This counterbalances their own shadow as an aid to concealment. In some animals, color changes during the life cycle to correlate with changes in habit. One species of mollusk, for example, is red while it feeds upon red algae in deep waters, but it becomes olive green as it migrates to brown and green algae in shallower locations. The mottled patterns of many young animals help to protect them at this vulnerable stage, and yearly rhythms of change in coloration occur in many animals of the colder latitudes, such as the ermine, Arctic fox, and ptarmigan; dark summer fur or feathers give way to white with the onset of winter.

Some animals can change their shades or even their colors to conform to those of their background. These changes are mediated through the eyes or the central nervous system. The effector organs are the chromatophores in the skin or elsewhere. Color changes of this kind have been most fully investigated in fishes, amphibians, and reptiles among the vertebrates and in crustaceans and the cephalopod mollusks among the invertebrates. Evidence that the capacity for pigmentary adjustments may be of lifesaving value to fishes has been obtained experimentally.

SELECTION

Of those species living in equilibrium with their environment, nearly all of the offspring resemble their parents in all the characteristics needed for survival. Offspring lacking these characteristics are eliminated. A polar bear born without fur in the Arctic would soon die, for it would not be protected against the cold. A cactus without spines might soon be devoured by animals.

Only those organisms best adapted to each environment are likely to survive and produce offspring. Those that are poorly adapted die young and leave few or no offspring. As a result, when adaptations are inheritable, each succeeding generation is a little better adapted than the previous one.

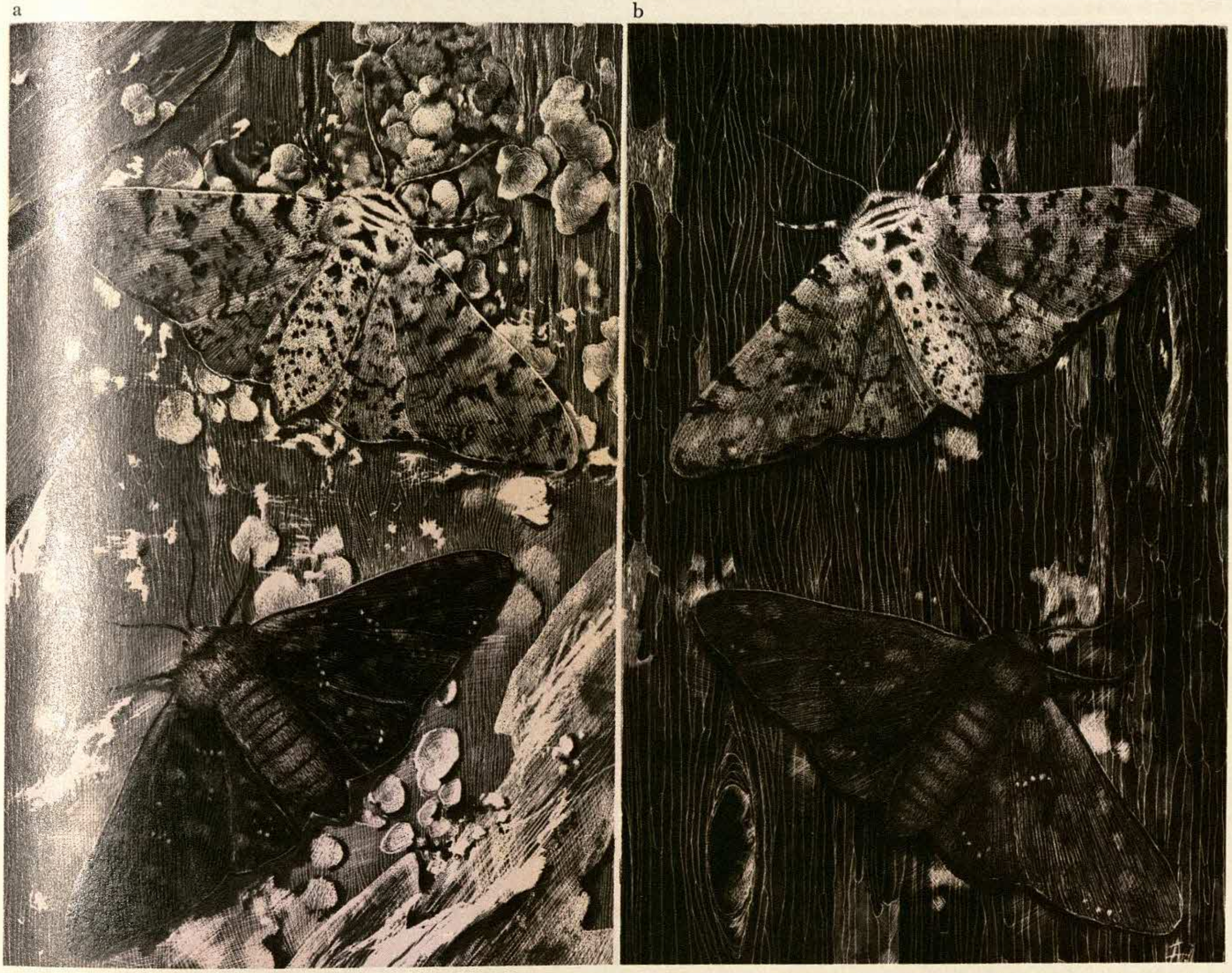
A recent study in England demonstrates how one species of moth adapted to living in an industrial region. Illustration 2 shows two forms of the peppered moth that lives in England. This nocturnal moth rests on tree trunks during daylight hours. The original form was light-colored, and it blended well with the lichens growing on the tree trunks, where the moth could rest in relative safety from predatory birds. Occasionally a black mutant form appeared, but it was so conspicuous on the light trunks that it fell easy prey to birds. As England became industrialized and soot blackened the trees, the light-colored moths became more readily visible to birds and survival of the black mutants was favored. Today, nearly all moths of this species in industrial areas of England are black, but light-colored forms still predominate in nonindustrial areas.

MUTATIONS

Adaptations that are inherited come about in only one way. A change, or mutation, occurs in the nucleic acid DNA. DNA, which exists in the nucleus of every cell of an individual, differs slightly among individual members of a species, but differs greatly from species to species. The chemical composition of DNA determines many of the characteristics of an organism—the spots on a butterfly's wings, for example, or the fur on a polar bear. Any change in the chemical composition of DNA may result in a change in inherited characteristics. In some cases the changes may be small or unimportant, but an owl butterfly without its spots or a polar bear without its fur would be in trouble.

The physical and chemical agents that cause alteration in the composition of DNA include x-rays, ultraviolet light, radiations from radioactive compounds, and some chemical compounds. These agents are known as mutagens. All living things are exposed to some extent to mutagens. If a DNA mutation occurs in eggs or sperms, then this mutation may be passed on to offspring. If the mutation is favorable (perhaps a thicker coat in the case of a polar bear or sharper spines in the case of a cactus), the offspring will be more likely to survive and produce additional offspring than will other members of the species. If the mutation is unfavorable, the offspring will be less likely to survive. In this way adaptation and selection act on the raw material provided by mutations; the species, improved with each generation, comes closer to perfect adaptation to its environment. The species' chances for survival increase, until such time as large-scale changes alter the environment.

2

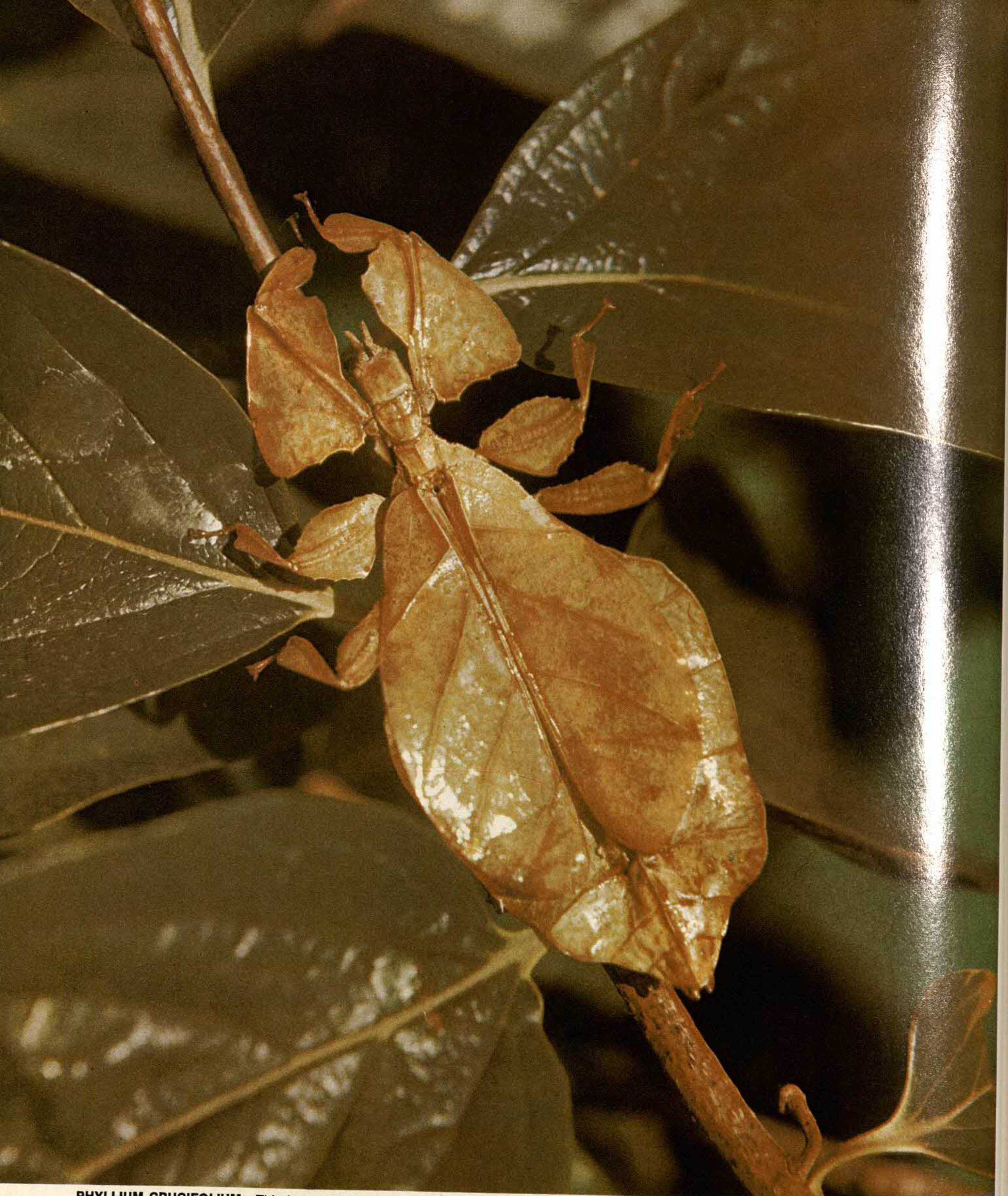


INDUSTRIAL MELANISM—The peppered moth, *Biston betularia,* is common in England. Moths light in color but mottled with black flecks are almost invisible when they rest on lichen-covered tree trunks, but black specimens are conspicuous (Illustration 2a). On soot-covered tree trunks, the light specimens are conspicuous, while the dark ones are difficult to see (Illustration 2b). The black form was almost unknown until industrialization favored its survival by blackening trees with soot.

SAFETY OR DANGER?

Being perfectly adapted to a particular environment can have its element of danger if the species cannot re-adapt when the environment changes. The history of the Earth shows that the environment is changeable. The climate of Antarctica was once warm enough to support the growth of ferns; but Antarctica is now covered by an ice cap, and ferns cannot survive there. The many fossils of extinct species indicate that many organisms could not adapt to changing conditions and died out.

On the other hand, the many environmental changes that occurred in the past made it possible for new species to evolve through the processes of mutation and selection of those mutations best adapted to the changed environments. For a billion years life has evolved from a few simple forms to the many forms that live today.



PHYLLIUM CRUCIFOLIUM—This insect (Phasmatida) closely resembles a leaf in shape and color and can easily camouflage itself to escape from predators. Camouflage is one of the applications of Darwin's theory of evolution according to which characteristics enabling a species to adapt to its environment allow the species to survive and pass the same characteristics to another generation.

EVOLUTION OF SPECIES

difference, resemblance, and classification

Every individual is different in some way from every other individual. This is true not only of human beings but of other animals and of plants as well. It is also true that every individual resembles other individuals to some extent. The degrees of difference and of resemblance permit the classification of living things into groups, the members of each group resembling each other more than they do members of other groups.

The classification of living things used by biologists today is based on one developed by Carolus Linnaeus, a Swedish botanist who lived in the eighteenth century. The group that he used as the basis for his work is the species.

CHARACTERISTICS OF A SPECIES

With the exception of some plants and animals domesticated by man, a species consists of individuals that resemble each other a great deal. To the casual observer a species may appear to consist of identical individuals—two polar bears look very much alike, two tigers look very much alike, and so do two silver maple trees.

The resemblance of members of a species to each other is due to the fact that they all have the same ancestry; that is, they evolved from a common ancestor in the geological past. Because of this, all members of a species are related, and they can and do breed with each other. This tends to keep the characteristics of a given species constant for many years. Polar bears living today look like polar bears that lived a thousand years ago, and one might predict that any polar bears living a thousand years from now will look like those existing today.

The uniformity of a species is maintained by another factor: members of one species usually cannot breed with members of other species and produce fertile offspring. A mule, which is the offspring of a cross between a female horse and a male donkey, is a strong, sturdy animal, but it is sterile and cannot breed with horses or donkeys or even with other mules. In this way the species of horses remains pure and does not receive hereditary material from donkeys; and donkeys, likewise, remain free of horse genetic material.

Linnaeus and the biologists who followed him delimited a species solely on the basis of anatomical characteristics of its members. Today, although there is no clear definition of a species that is agreed upon by all biologists, a species usually is considered to consist of a group of organisms that are capable of breeding with each other but incapable of breeding with other groups.

This does not mean that there is no variation within a species or that species remain the same forever. There are even some exceptions to the general rule that no fertile hybrids can be produced from crosses between species.

THE ORIGIN OF NEW SPECIES

The natural variability that exists within any one species is the primary source of new species. The great variety of genetic material in a wild species is not always obvious, for only those individuals that are best adapted to the environment to which they were born survive; those that deviate from this norm usually die. Abundant variety can be seen readily, however, in man's domestic plants and animals in which he has encouraged the development of varieties that probably would not continue to exist unprotected in nature. Cabbage, cauliflower, Brussels sprouts, and broccoli have different forms but are all members of the same species, *Brassica oleracea.* Collies, fox terriers, poodles, and dachshunds are all dogs and are all members of one species, *Canis familiaris.*

Such variations are encouraged in nature only when the environment changes or when a species moves into new areas that are slightly different from their old areas. The natural selection results in the survival of those individuals that are best adapted to the new conditions. If the environmental changes occur gradually and continue long enough, each succeeding generation will differ from the preceding one, and over thousands of generations the accumulated changes will result in offspring so different from their early ancestors that they constitute a new species.

When two groups within the same species are kept from breeding with each other for long periods of time, they frequently evolve into separate species. Such reproductive isolation occurs if groups within a species are separated by large mountain ranges, large bodies of water, or other barriers. Oceanic islands often have their own peculiar species that evolved there in isolation. The Galapagos Islands in the Pacific Ocean have many species of animals that are found nowhere else in the world but that seem to be descended from the animals of South America, the nearest continent. It was Charles Darwin's study of these islands and their inhabitants that led him to his theory of the origin of new species from pre-existing species.

Examination of fossils and of living organisms has reconfirmed Darwin's theory. If sufficient fossils are found, it is possible to reconstruct the family tree of a group of related species. Today only two species of elephant exist: the Indian elephant (*Elephas indicus*) and the African elephant (*Loxodonta africana*). Many elephants died out, possibly as a result of overspecialization or climatic changes.

THE SPEED OF EVOLUTION

Some species have existed for millions of years without changing; others produced new species in a few thousands of years —a relatively short period of time, geologically speaking.

The rate at which evolution proceeds depends on several factors: the mutation rate within the species, the rate at which the environment changes, and the generation time of the species. The mutation rate depends in part on the exposure of the organisms to ultraviolet light, radioactivity, and other mutagenic agents. Because the intensity of these agents is greater in the air than in the depths of the sea, evolution has proceeded more rapidly on land than in the ocean. The sea provides a more nearly constant environment than does the land with its changing seasons and changing climates; for this reason also, the sea has fostered fewer new forms than has the land. The shorter the generation time, the more rapidly adaptation and selection can provide new species. It is not surprising, then, that the insects with their terrestrial habitats and their short generation times (a few days in some species) are not only among the most highly evolved living things, but also have more species than other major groups of organisms.

PHYLOGENY

reconstructing the history of a species

Research in the field of evolution is not unlike detective work. The paleontologist searches for clues and collects as many of them as he can. With the discovery of each new clue, he can add a little more to the story he is trying to reconstruct. With luck, enough clues will be found to round out a complete story.

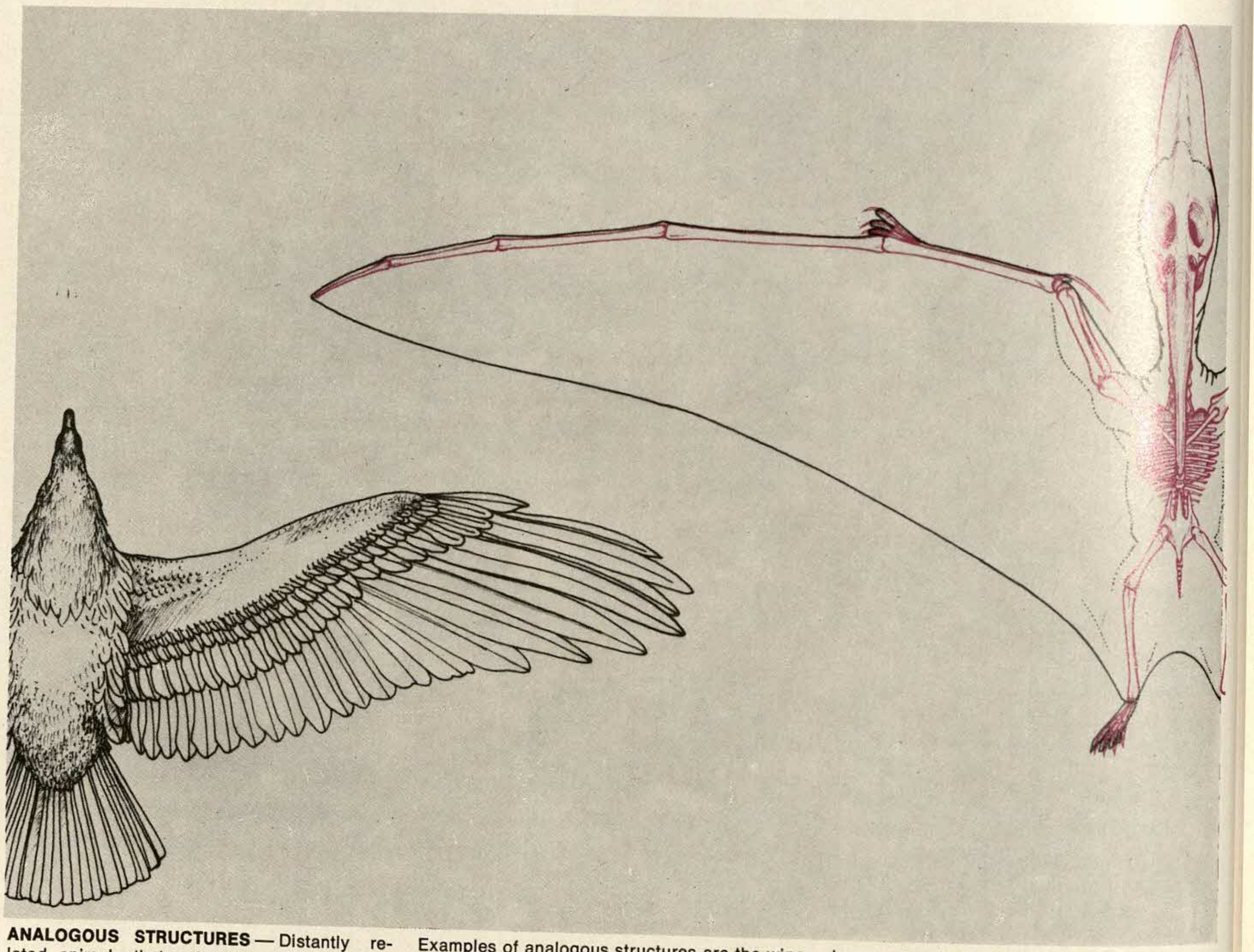
The clues in the field of evolution are fossils and the rock strata in which they are found. A worker in this field tries to reconstruct the phylogeny, or evolutionary history, of a particular species of plant or animal. When this has been accomplished for several species, the phylogeny of a family of related species can be worked out; then the phylogenies of larger groups—orders, classes, and phyla—can be constructed.

Animal fossils often consist only of bones or shells, for the soft parts usually decay quickly. From these fossils it is possible to determine several things about an animal: its size, its diet, some of its habits, and its relationships to other organisms. Morphology, the study of form and structure in plants and animals, is vital to problem-solving in phylogeny.

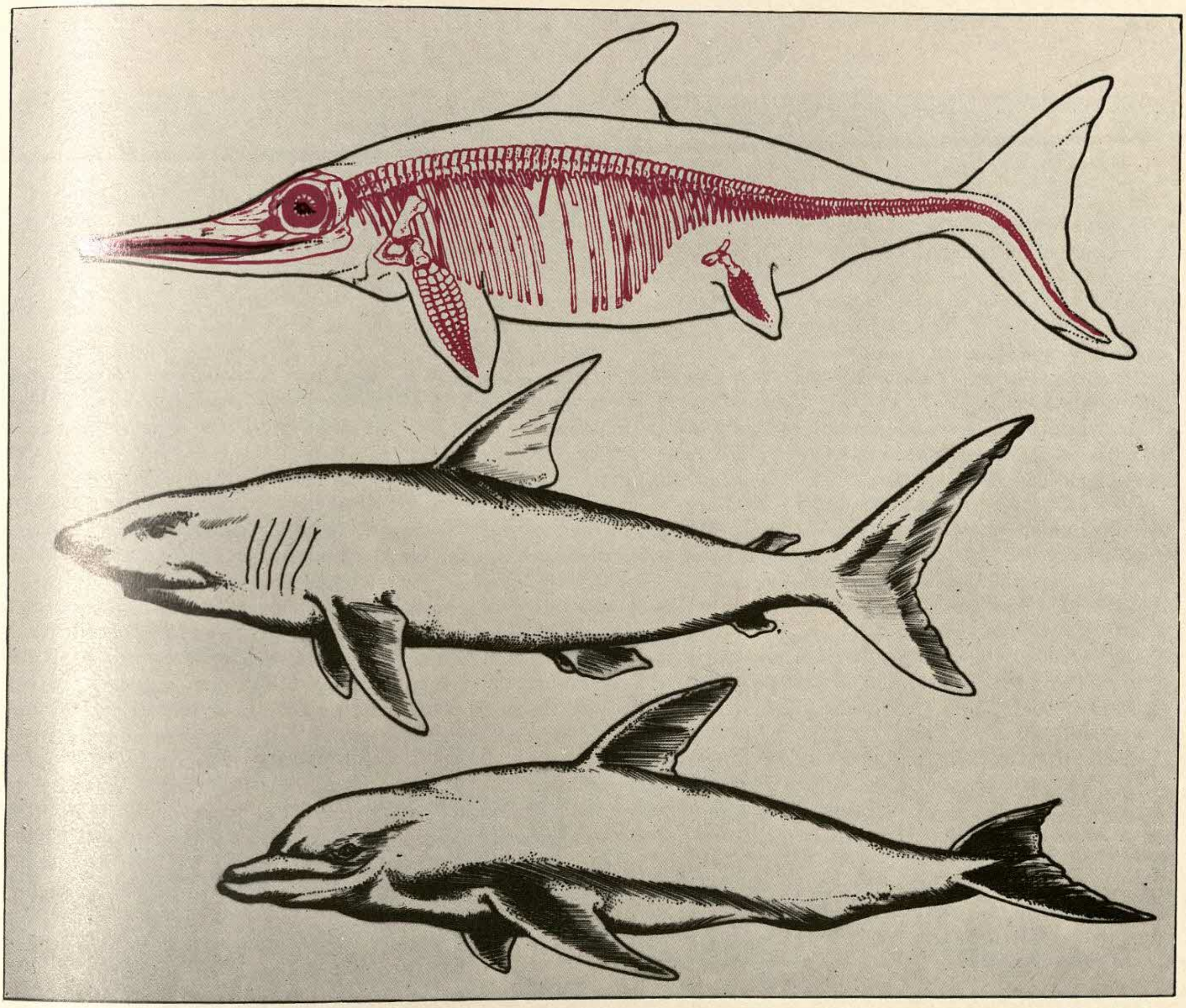
PHYLOGENETIC RECONSTRUCTIONS

One of the aims of paleontology—the study of life in the geological past—is to develop an evolutionary tree that encompasses all species. This tree includes not only living organisms but also their ancestors as far back as the first living things. The job is such a large one that a paleontologist can work with only one or a few groups of plants or animals in his lifetime.

The phylogeny of a species is deter-



ANALOGOUS STRUCTURES—Distantly related animals that enter the same new environment often adapt in similar ways. Organs that have similar functions and shapes but that evolved independently are *analogous.* Examples of analogous structures are the wing of the pterodactyl, an extinct flying reptile, and the wing of an eagle, a modern bird. The wings are constructed differently, the pterodactyl wing consisting mostly of a thin membrane stretched between the body and the bones of the forelimb and the eagle wing consisting mostly of feathers that grow from the forelimb. Both wings are flat structures that permit the animal to fly.



CONVERGENT EVOLUTION—Aquatic animals that are active swimmers require a streamlined shape for easy, quick movement through water. This illustration shows three unrelated animals that have similar shapes. The upper illustration shows an extinct marine reptile, *Ichthyosaurus;* a modern shark, a cartilaginous fish, is illustrated center; and the dolphin, a marine mammal, is in the lower illustration.

mined only by long and patient study of a vast number of fossils. The age of the fossil may be determined by radioactive dating; the age of the geological stratum in which the fossil was found may give the same information. When possible, the paleontologist uses both methods as checks against each other.

When the ages of several fossil species have been determined, the species can be arranged in chronological order. The paleontologist may wish to assume tentatively that the oldest fossil was the earliest species to evolve and the youngest was the last; but this is not necessarily so. Instead, it may be that old fossils of the species presumed to be the youngest have not yet been found. The paleontologist must always be ready to change his theories when new evidence is uncovered.

When the ages of fossils and the order of their appearance have been established with some degree of certainty, the paleontologist looks for clues that could establish relationships among these species. He must examine bone structure, numbers and kinds of teeth, general body form, and any other clues that may be available to determine the most likely phylogeny for the group he is studying. The conclusions that he draws may change his ideas about the relative ages of the species. If there is only a single line of descent, his task may be relatively easy; but if several main lines of evolution developed within the group, it may be hard to determine the number of lines of evolution and which species belongs to which line. In view of the uncertainty of the evidence, phylogenetic conclusions must be tentative. Knowledge of morphology and paleontology is far more detailed in vertebrates than in any other group of similar size.

PRECAMBRIAN TIME

the longest geological era

The giant strides made by science and technology in the last few decades give the impression that there are few discoveries still to be made about the universe. This is far from being true, for a study of the history of the Earth, especially its most ancient history, shows that not many of the facts are known.

How the Earth came to be formed is still a cause for debate. One theory states that it condensed from a giant cloud of hot stellar gas. The outer part of the Earth cooled into a solid crust that was subject to such violent forces as earthquakes and volcanic action. Another theory states that the Earth originated from a cold cloud of gas and dust particles—and there are still other theories. Regardless of which is true, however, life would not have originated until a firm crust and the oceans had formed.

Exactly when life appeared on Earth is not known with certainty. It is certain that some forms of life were present 3 billion years ago, for fossils of organisms resembling algae have been found in rocks estimated to be that old by radioactive methods. Life originated in the sea and has undergone a continuous evolution since that time.

A MYSTERIOUS ERA

Geologists divide time into geological eras. Beginning with the oldest and proceeding to the most recent they are: Archeozoic, Proterozoic, Paleozoic, Mesozoic, and Cenozoic. The Archeozoic and Proterozoic eras often are considered as one long era, the Precambrian, which began at least 3 billion years ago and ended about 600 million years ago at the beginning of the Paleozoic era. The Precambrian was so called because it immediately preceded the Cambrian period, the first period within the Paleozoic era.

The Precambrian extended over such a long period of time that it exceeded in length all of the periods that followed. The existence of fossils in late Precambrian rocks is well established, although there are few of them compared with later eras. In the earliest strata of Precambrian times, fossils are extremely scanty but not unknown.

The fact that no fossils have been found in some of the early strata does not necessarily mean that life did not exist then. First, the Precambrian rocks, being the oldest in existence, are overlain by deep sediments in many parts of the world; it is only where they are exposed (as in eastern Canada) or lie near the surface that they can be examined for fossils. Second, the first organisms must have been simple microorganisms that disintegrated completely when they died and left no fossils.

Third, any fossils that were preserved in rocks as old as the Precambrian were exposed subsequently to the same forces that the rocks received. Some rocks were melted by the Earth's heat and later solidified. Others were deformed by great pressure from the weight of younger layers of sediment accumulating above them or from the horizontal movement of large blocks of strata; chemical reactions with compounds seeping into the rocks changed their composition. Such changes destroy fossils. Old fossils, like those of the Precambrian, are more likely to have been destroyed than those of more recent times, for they have had a greater chance of being exposed to destructive forces.

Finally, sedimentary rocks of marine origin that have lasted from those earliest times are relatively rare. Most sedimentary rocks of that age appear to have been formed by sediments of continental origin. Because life probably originated in the seas, few fossils of the earliest life-forms would be likely to exist today.

PRECAMBRIAN ROCKS IN THE UNITED STATES

Rock from the earliest era of Earth's history probably underlies all younger rock, but there are large areas that have no cover of later deposits, either because there never was one or because it was destroyed by erosion. All exposed Precambrian rocks in the United States belong to the group that lost their cover as a result of orogeny, the folding of the Earth's crust in mountain formation of later geological time. The result of such upheaval is destructive erosion. The mountains themselves have practically disappeared from the largest of these areas in northern Minnesota, Wisconsin, and Michigan, where only residual hills survive. The Piedmont plateau and the Great Smoky Mountains are parts of a smaller area composed largely of Precambrian rocks. Despite their magnitude, the Adirondacks of New York, the Green Mountains of Vermont, and the White Mountains of New Hampshire are only the Precambrian core rock of former ranges. Many ranges of the Rocky Mountain system also show exposed Precambrian core rock.

Outcrops of Precambrian rocks in the central lowlands and Great Plains include the St. Francis Mountains of Missouri, part of the Black Hills of South Dakota, the Wichita and Arbuckle mountains of Oklahoma, and the Llano uplift in Texas. The Grand Canyon of the Colorado was cut deep into the Precambrian basement. Attempts to correlate formations, orogenies, and erosion cycles of widely separated regions have been unsuccessful. The best classification in North America involves the Canadian Shield.

THE PRECAMBRIAN SEAS—In this cutaway view of a shallow Precambrian sea, the presence of life in the sea is suggested by the greenish tint that the water takes from the unicellular algae that live in it. Scattered here and there on the seabed are larger algae. The dry land is barren, for it has not yet been colonized by living things.

THE ARCHEOZOIC ERA

early rock formations

A highly detailed account of the Earth's history begins only about 600 million years ago, in the Cambrian period. Precambrian time is divided into two eras—the Proterozoic and the Archeozoic—of which the Archeozoic is the earlier.

The Archeozoic (or Early Precambrian) era began at least 3 billion years ago and lasted for about 1.5 billion years, as long as the whole of the rest of the world's history. A few fossils have been found from this time, but they represent only simple organisms.

Among the best-known and largest expanses of Precambrian rock exposed at the surface, or covered by only shallow deposits, is the Canadian Shield, which includes eastern Canada and most of Greenland. Every continent has its own shield, a stable formation consisting mostly of Precambrian rocks. The Archeozoic rocks in this vast area of Canada consist largely of granite, an igneous rock, and gneiss, a metamorphic rock.

Also present are schists, quartzites, and other crystalline rocks. Contained in these rocks are valuable mineral ores that yield gold, silver, platinum, copper, nickel, cobalt, iron, lead, and zinc.

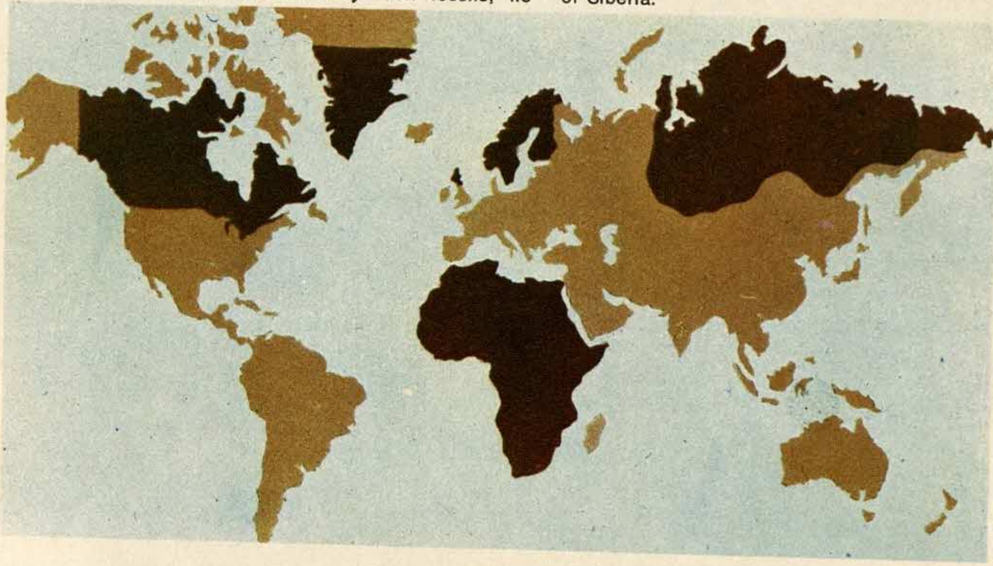
The Canadian Shield includes most of northeastern Canada and the greater part of Greenland. It extends into the United States west and south of Lake Superior and into northern New York State. Of the total area of about 2,780,000 sq mi, about 1,905,000 are in Canada; about 800,000 are in Greenland, and 75,000 are in the United States.

The rock structures indicate that there once were great chains of mountains in the shield. By the end of Precambrian time, however, the mountains had been eroded to a relatively low level that was later invaded by the sea.

---

1 **THE ARCHEOZOIC SYSTEM**—The rocks formed during a particular period compose a system that corresponds in name to the period itself. Thus, the rocks which formed during the Archeozoic period are called the Archeozoic (or Early Precambrian) system. Most of the rocks of the Earth's crust belong to this system, but because they lack fossils, lie at an enormous depth, and are difficult to date, not a great deal is known about them.

The map shows (in brown) the areas of the Archeozoic system that have been studied in some detail. They comprise the Canadian Shield, southern Greenland, the Scandinavian Shield, Scotland, the African Shield, and part of Siberia.



2

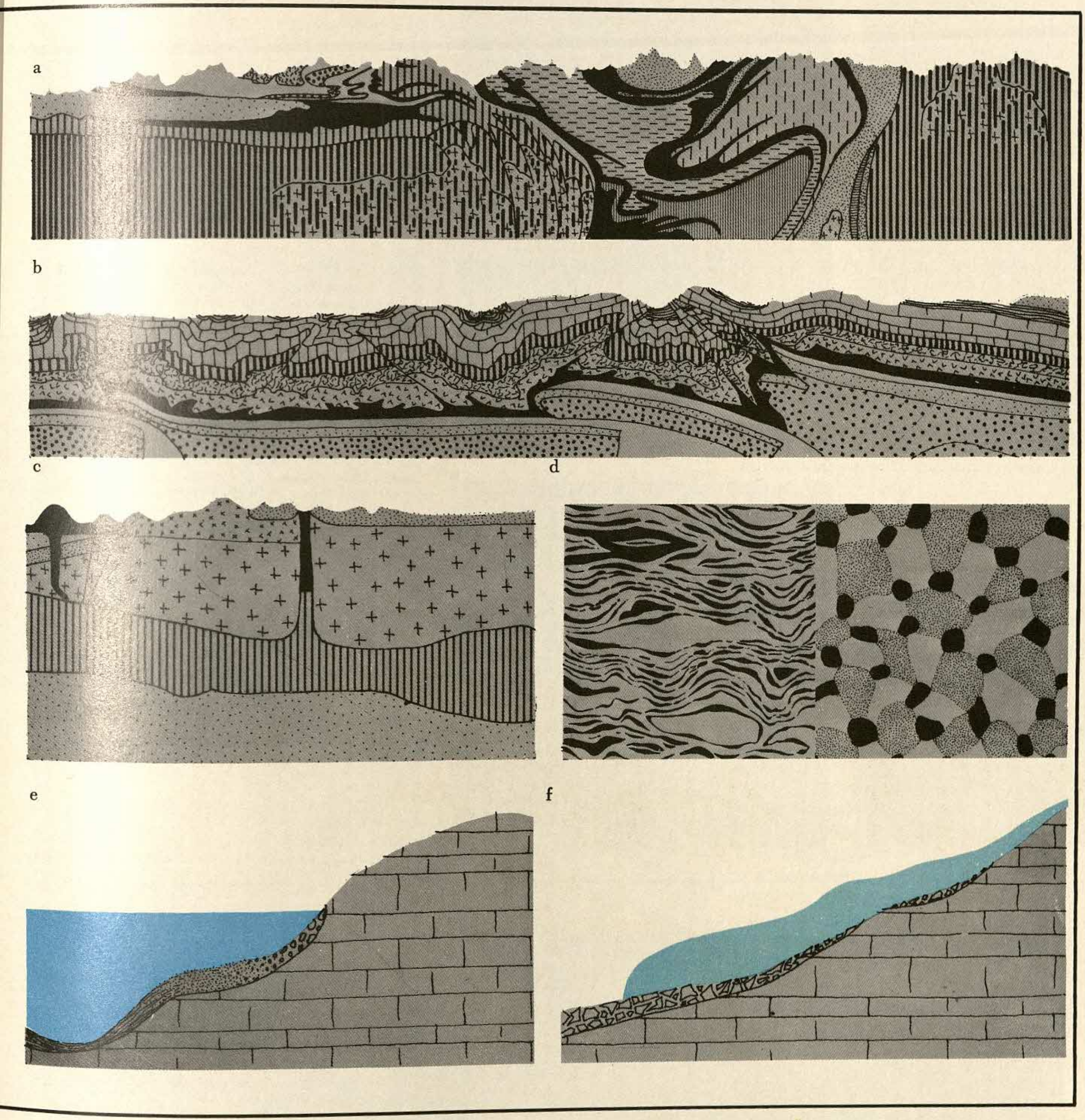
RECOGNIZABLE GEOLOGICAL PHENOMENA—This series of diagrams illustrates geological phenomena characteristic of the Archeozoic period and most widespread both in space and time. Illustration 2a shows orogenetic (mountain-building) phenomena. During the Archeozoic period a number of important mountain ranges arose. Erosion has now left only slight traces of these. The next diagram (Illustration 2b) shows folding phenomena. Many strata have been subject to the thrust of powerful forces that have thrown them into folds. The thrusts usually occur in series and not all at once, and it is not always possible to reconstruct the exact sequence of events.

Illustration 2c shows intrusions of magma, the hot, molten rock in the Earth's crust or from deeper regions. Magma (shown in black) may be forced up, to intrude between the rocks near the surface where it solidifies. While the magma is still warm, it may react chemically with the rocks with which it comes in contact, and thus may change its chemical composition.

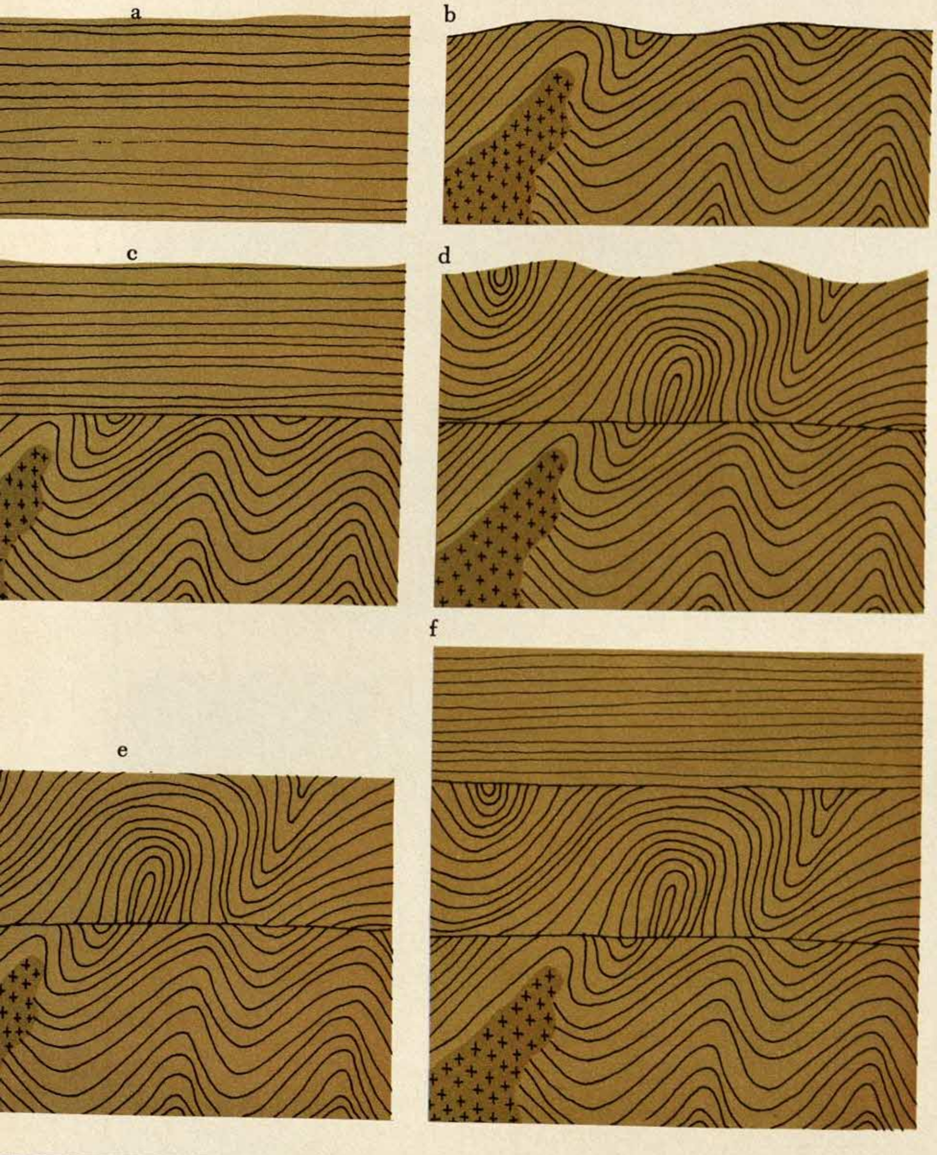
Metamorphism (shown in Illustration 2d) is a result of the physical forces that have been brought to bear on rocks and of the chemical changes that occur in them. Rock masses subjected to these physical and chemical agents are said to be metamorphosed. Their macroscopic appearance changes, and microscopic alterations occur as well. The greatest changes are seen in the shape of the crystals: roundish shapes often become elongated, as if they had been laminated. The diagram shows crystals before and after undergoing metamorphosis. Chemical composition of the crystals may change because of reactions between several components of the rock, or between them and external agents such as intrusive magma or minerals introduced by infiltrating water.

Illustration 2e is a diagrammatic representation of sedimentation. Much of the Archeozoic system is made up of sedimentary material. In later ages sedimentation was caused mostly by the sea's action, but the sedimentation of the Archeozoic era often was the work of inland lakes or of glaciers.

The Archeozoic system includes very extensive glacial deposits called moraines. The Canadian Shield shows evidence of having been covered by a continental glacier. One product of glacial erosion is tillite (boulder clay). This is pushed forward as the glacier advances and is deposited as moraines when the glacier melts (Illustration 2f).


a
b
c
d
e
f

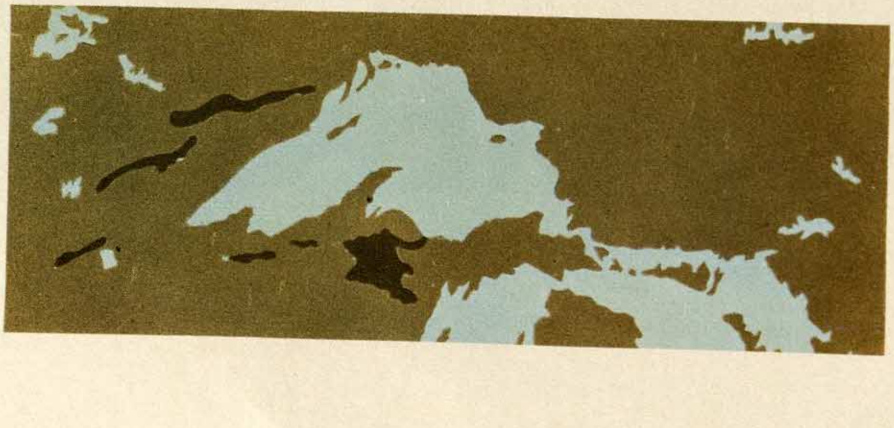
3



A VERY COMPLEX HISTORY—Some of the southern part of the Canadian Shield belongs to the Archeozoic system. Thorough geological study has revealed its history, and this is reconstructed in the series of diagrams shown here. The earliest times saw the formation of horizontal strata of tuff and lava from volcanic eruptions (Illustration 3a). Strata of these rocks alternated with strata of sediments from accumulated detritus. Some of these strata contain such high percentages of iron that it can be extracted economically; in fact, the richest iron deposits in the world are in this area.

The horizontal strata were thrown into folds that permitted the intrusion of magma (shown in darker color, Illustration 3b). The tops of the folds were eroded away, leaving a flat upper surface. Fresh sediment was deposited above the folded strata (Illustration 3c). This sediment originated in erosion caused by rivers and glaciers. These sediments contain organic remains of primitive organisms.

Illustration 3d shows the upper strata, which were folded by geological forces. Later erosion flattened the surface again (Illustration 3e). Finally (Illustration 3f), in the Proterozoic (or Late Precambrian) era new sediments were deposited on top of the older strata. No important foldings took place later in the Canadian Shield. This region of the Earth, therefore, has been quiescent for about a billion years; it is typical of many shields, including those of Scandinavia and Siberia.



VERY ANCIENT DEPOSITS—This map shows the distribution of the iron deposits that formed in the Archeozoic era in the region of Lake Superior. The deposits, marked in darker color, were laid down during the Archeozoic era and are now mined. This area is in the southern part of the Canadian Shield. Most shields are flat areas with few topographical features.

SPECIALIZATION FOR SURVIVAL

first steps up the evolutionary ladder

THE GREEN REVOLUTION—If the first step in evolutionary development was increase in size, the second—a giant step—was the occurrence of photosynthesis. At some point in Precambrian time, perhaps 2 billion years ago, the first green algae appeared on Earth. These were very simple one-celled organisms, probably much like the algae shown in Illustration 1a, but they contained the remarkable substance chlorophyll, which enabled them to capture energy from the sun (Illustrations 1b and 1c), somewhat as a mirror captures the sun's light. The algae used this energy to carry out a complex chemical reaction—the combination of carbon from carbon dioxide and hydrogen from water to build carbohydrates. In the process, free oxygen was released.

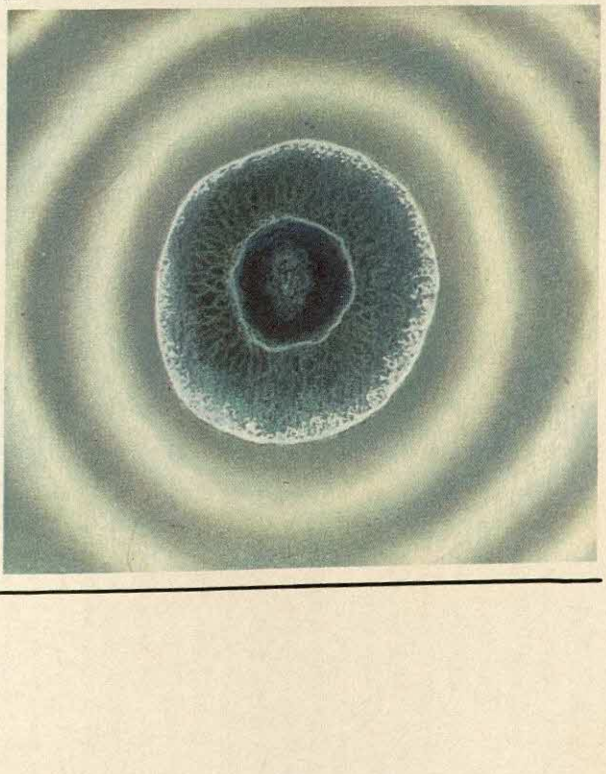
1b

1a

The first algae capable of photosynthesis began creating the supply of oxygen and organic food that would, much later, support more complex forms of life and eventually, man.

Unicellular organisms such as the algae shown in Illustration 1a could extract energy from only one source: nutrients that entered the cell by diffusion. The algae containing chlorophyll had a much better chance for survival because that substance was able to harness energy from an additional outside source: the sun.

1c



An understanding of life and how it has developed is essential to the study of evolution. It is helpful to think of a living organism as a mechanical system or factory that performs some useful function. The imaginary factory can serve as a model of any form of life, one-celled or many-celled.

It is relatively easy to build a model of a machine and to learn, from the model, how the different parts serve different purposes. Living organisms are so complex and variable that it is impossible to build models that represent them accurately, but even a greatly simplified model may prove useful. The romantic nature lover may rebel at describing a bird as a machine for flying, with a motor that converts fuel into energy; but this kind of concept has contributed to the increase of scientific knowledge.

A BILLION YEARS OF EVOLUTION

The earliest life-forms known existed in Precambian time; they are known from fossils found in rocks at least a billion years old. An examination of these fossils shows that life had already made colossal progress. One-celled organisms had perfected techniques of absorbing nutrients from the environment and of eliminating wastes. Many-celled organisms had developed from single-celled ones. This last step is of greater significance than the evolution of mammals from reptiles. The life of a unicellular organism is a combination of chemical reactions, while the life of a multicellular organism is primarily a complex mechanical system better designed for survival. In a unicellular organism, destruction of one cell obviously means death. Higher forms can make adjustments and live. A study of successive phases in the evolutionary process shows multicellular life-forms developing increasingly complex systems capable of assuring greater chances of survival in an increasingly hostile environment.

A MODEL OF A CELL—Defining living matter even as simple as a unicellular organism is a difficult task that can go outside the boundaries of the strictly scientific. In these illustrations, the cell is first represented as a sphere containing a library and a laboratory (Illustration 2a). A liquid substance flows around the cell and can pass into it through openings in the cell wall. The organism extracts useful materials from this fluid, and eliminates waste products through the same openings in the wall. The materials extracted from the fluid are used in the laboratory, according to information recorded in the books in the library. (No attempt has been made to represent the mysterious something that reads the books and transfers the knowledge to the laboratory.) The work that goes on in the laboratory has two purposes: (1) support and maintenance of the enclosing wall, the library, and the laboratory, and (2) duplication of the entire structure.

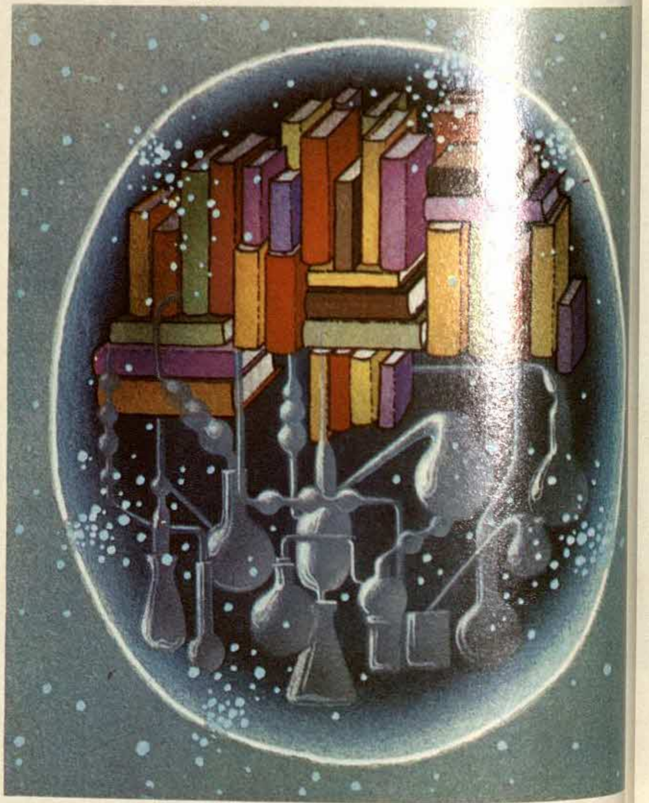
Illustration 2b shows the sphere with more books in the library and more apparatus in the laboratory. The next step is the most complicated; the duplicated parts become isolated from each other and the sphere splits in two, each part containing a complete library and a fully equipped laboratory (Illustration 2c). While this is happening, work continues in the laboratories. Before long, the two units become four, where the same work is carried on at the same rhythm. This process represents mitosis, the series of changes through which the nucleus passes during ordinary cell division.

2a

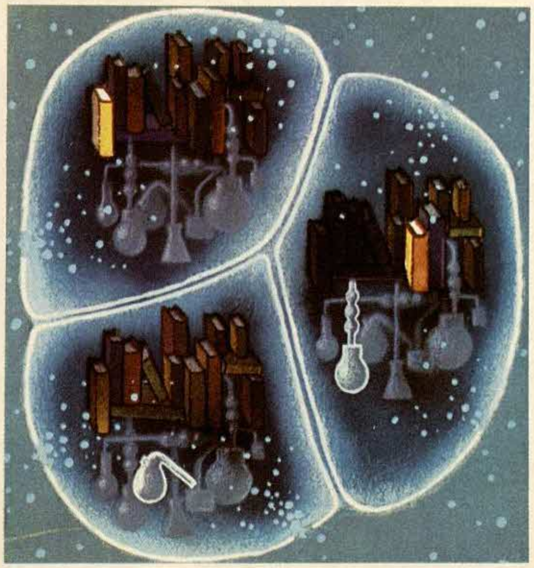
At all times, the operations carried out in the laboratory are determined by information contained in the library, as the processes of growth and reproduction carried out within the living organism are determined by the chemical structure of substances in the cell.

2c

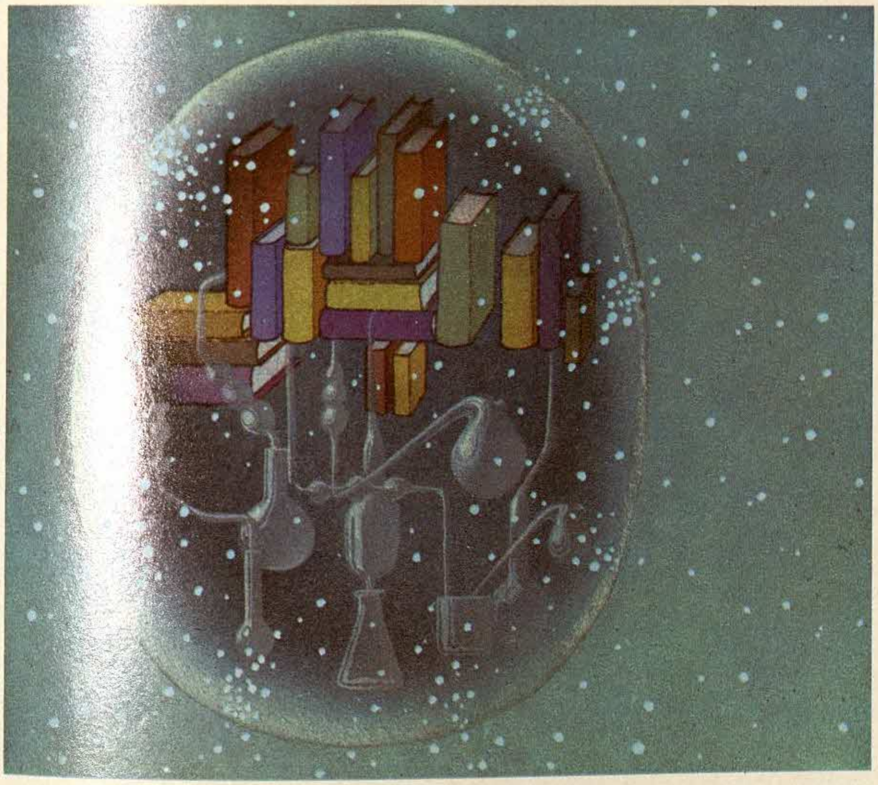
2b



4



3



A PRIMITIVE WAY OF OBTAINING FOOD—The very first forms of life, simple one-celled organisms such as the one this model represents, could not move about in search of food. Obviously, the later, more complex organisms that developed some method of locomotion had a great advantage over these immobile ones.

The unicellular organism represented by the model remained in one place or drifted passively with the liquid in which it was immersed. The liquid entered the cell by diffusion through the thin but tough membrane that formed the cell wall, and the organism assimilated certain nutrients dissolved in the liquid. If the liquid happened to be rich in substances the organism could utilize, the organism thrived and reproduced. If not, it died.

The earliest forms of life were dependent on the presence of a few easily utilized nutrients in the environment, until a remarkable new development—photosynthesis—made it possible for them to break down more complex chemical compounds.

FROM ARTISAN TO INDUSTRY—Illustrations 2 and 3 show, in greatly simplified form, the life processes carried on inside the single cell of a very primitive living organism. The assimilation of food, the elimination of wastes, and the complicated process of reproduction all took place within the confines of the cell wall, while the organism struggled to survive in a hostile environment.

This model represents the change that took place when many-celled organisms developed from single-celled ones. The artist has shown three spheres joined together in a cooperative effort to carry on their work. Each maintains the characteristics of the original sphere—a library and a completely equipped laboratory—but each concentrates on just one part of the total manufacturing process. In a somewhat similar fashion, each cell within the body of the multicellular organism has its own function to perform.

Actually, even a very small multicellular organism has millions of cells, and instead of just one cell specializing in each function, thousands of identical cells form a group. Larger and more complex forms of life have more different kinds of cells, as well as more of each kind.

It is obvious that the multicellular organism has had a greater chance for survival than the unicellular one. In the latter, the destruction of one cell means death. In the multicellular organism, many cells can be destroyed without causing the death of the organism. In relatively small and primitive forms of life, the dead cells are tolerated, and the life processes are carried on by the undamaged cells around them. In higher forms of life the dead cells are eliminated from the body and eventually replaced by new ones. In either case, life goes on.

THE LATE PRECAMBRIAN ERA

a time of slow, but significant, change

Major geologic time divisions are, as a rule, subdivided on the basis of extraordinary events that are known to have occurred within them. Precambrian time was relatively rich in important events, but these events tended to be drawn-out rather than cataclysmic, making it difficult to define precisely the end of one period and the beginning of another. During Precambrian times, biologic developments reached the critical stage at which living forms assumed the characteristics that made possible their success and invasion of all terrestrial environments. Still, the extreme scarcity of fossils makes the drawing of precise temporal subdivisions practically impossible.

Nevertheless, it is customary to subdivide the interval between Eozoic times, extending backward past the time of formation of the oldest known rocks some 3.5 billion years ago, and Paleozoic times into two great eras: the Archeozoic, or Early Precambrian era, which is assumed to have lasted some 900 million years, and the Proterozoic, or Late Precambrian era, which lasted some 800 million years and ended with the beginning of the Cambrian period some 620 million years ago. In the wake of the Late Precambrian era the evidence for geologic and biologic events suddenly becomes much clearer and far more abundant, permitting a more precise and detailed subdivision of the Paleozoic and later eras into periods and epochs.

LATE PRECAMBRIAN ROCKS

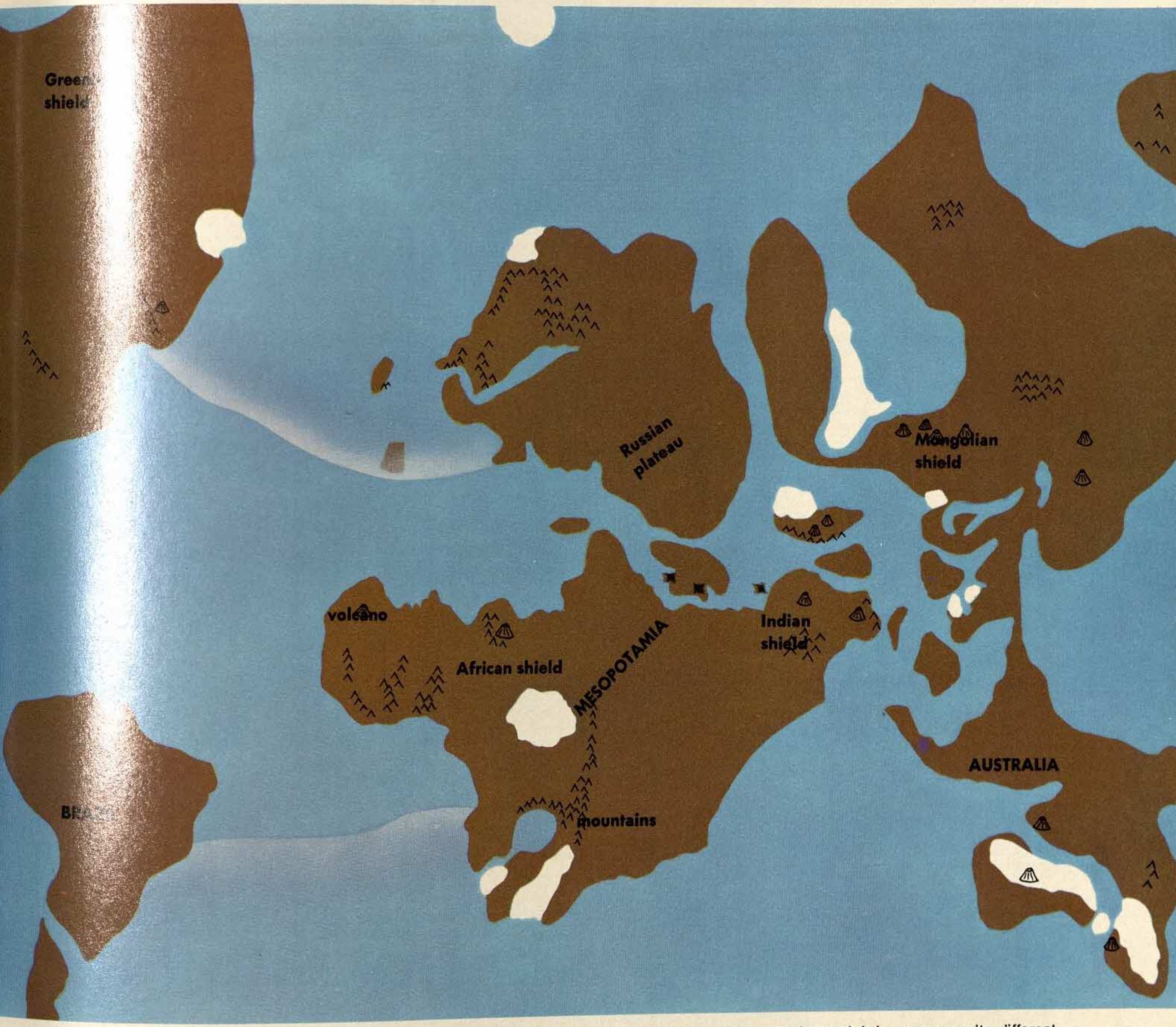
Rock units of Late Precambrian age are distinguished from Early Precambrian rock units by the fact that they are usually much less metamorphosed and crumpled than the latter. Also, the rock units of Late Precambrian ages are separated from the older, Early Precambrian rock units by a disconformity; that is, by a surface of erosion between adjacent strata, indicating that the process of sedimentation was temporarily interrupted. The separation is not always clearly visible, however. In some parts of the world, Early Precambrian and Late Precambrian strata appear to merge into one another, without clear evidence for a break in sedimentation.

The rock units representing the two eras may also be distinguished from one another by the fact that, unlike Early Precambrian sequences of rock units, formations of Late Precambrian age incorporate for the first time abundant strata of marine origin, implying that some of the land that is now dry was for the first time flooded by the sea in Late Precambrian times. These marine rocks also include a few organogenic strata; that is, layers formed through the accumulation of recognizable remains of living organisms.

The fact that Early Precambrian rock units are found to be usually more intensely folded and deformed than Late Precambrian rocks in the same geographic area must be attributed mostly to the discrepancy in age—to the fact that the older rocks were more frequently exposed to deforming forces than the younger rocks. However, it is also significant in this connection that the older rocks originated and existed at a time when the prevailing temperatures in the Earth's crust were slightly greater, implying a greater degree of plasticity. This, in turn, would have meant less fracturing and less opportunities for magmatic intrusion.

The relative abundance of volcanic rock as well as the occurrence of glacial deposits indicates that the last 200 million years of the Late Precambrian era were marked by pronounced volcanic action as well as by the spreading of ice caps similar to the one now covering most of Greenland. These existed in what are now Canada, Australia, India, South Africa, and elsewhere. Precambrian rocks are exposed over one-fifth of the land surface of the Earth.

THE SURFACE OF THE EARTH 750 MILLION YEARS AGO — This illustration shows the earth's surface as it may have appeared 750 million years ago. The map shows that the shapes of the continents were probably not substantially different than today. Nonethe-



less, the locations of mountain chains are quite different. All of today's mountain chains are missing. In other regions there are mountains that have since either disappeared or have been reduced to mere hills by the effects of erosion. The lack of vegetation on dry land in Late Precambrian times made it possible for erosion to level and obliterate most elevated landmarks shortly after their creation. The map also shows the locations of the great ice caps.

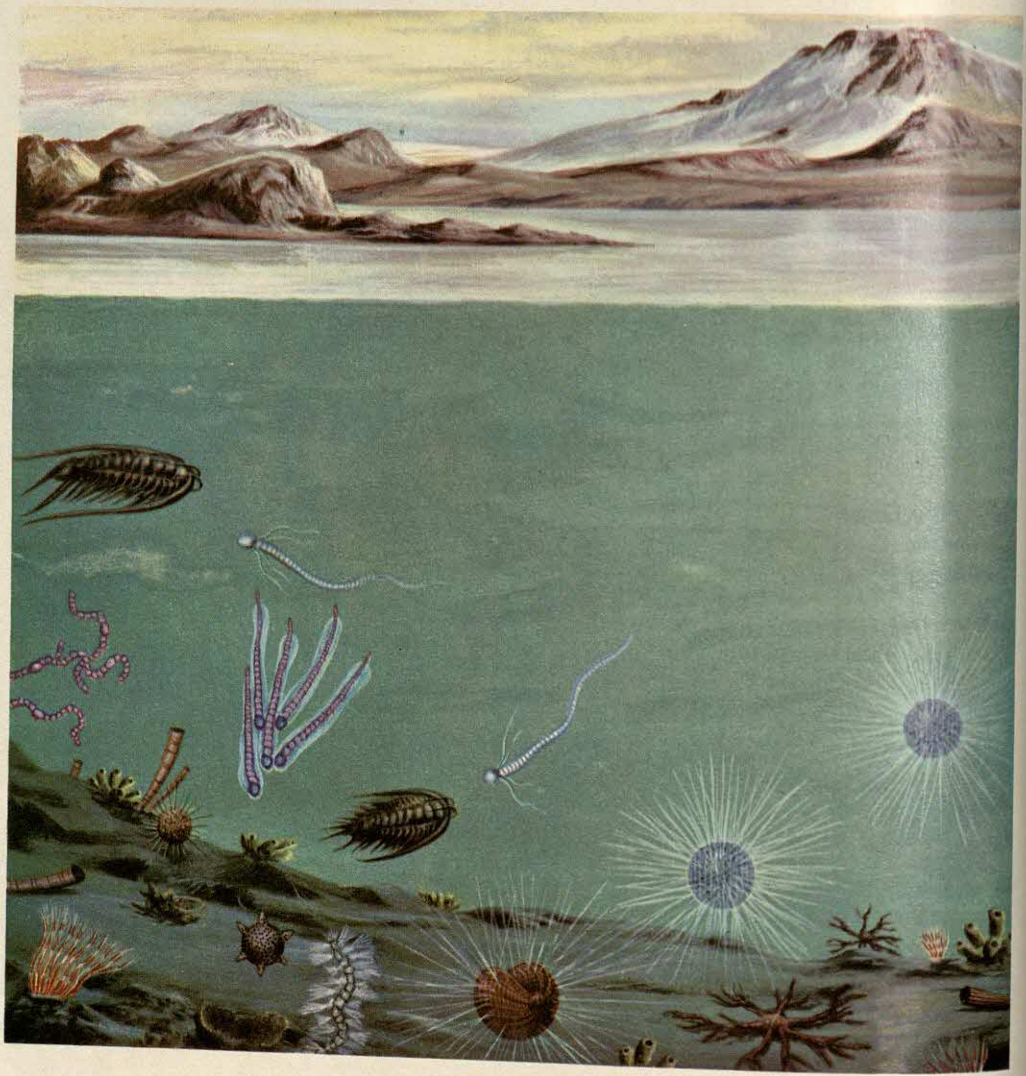
The Americas, Africa, and Australia appear already in their present shapes. Europe does not yet exist, and Asia appears quite different from Asia today. Most of Siberia is occupied by a large embayment of the sea. Where the Himalayas now rise there are small mountains that are destined to disappear before the present colossal mountain range appears.

LATE PRECAMBRIAN FLORA AND FAUNA

Unlike the rock formations of the Paleozoic and later eras, the rocks of the Late Precambrian era typically contain very few fossils of plants and animals, although it is commonly believed that during this era some organisms had already reached dimensions of several centimeters and, in exceptional cases, even a few meters. These relatively large dimensions imply that the organisms—primitive as they were—had progressed toward forms of far greater complexity than the forms of life existing at the close of the Early Precambrian era. It is quite proper to describe these organisms as large when it is realized that an organism one centimeter in length is considerably closer in dimensions to man than to a bacterium. Following the Late Precambrian era, evolutionary developments tended to be directed toward diversification and differentiation of species rather than toward an increase in the size of the existing forms of life.

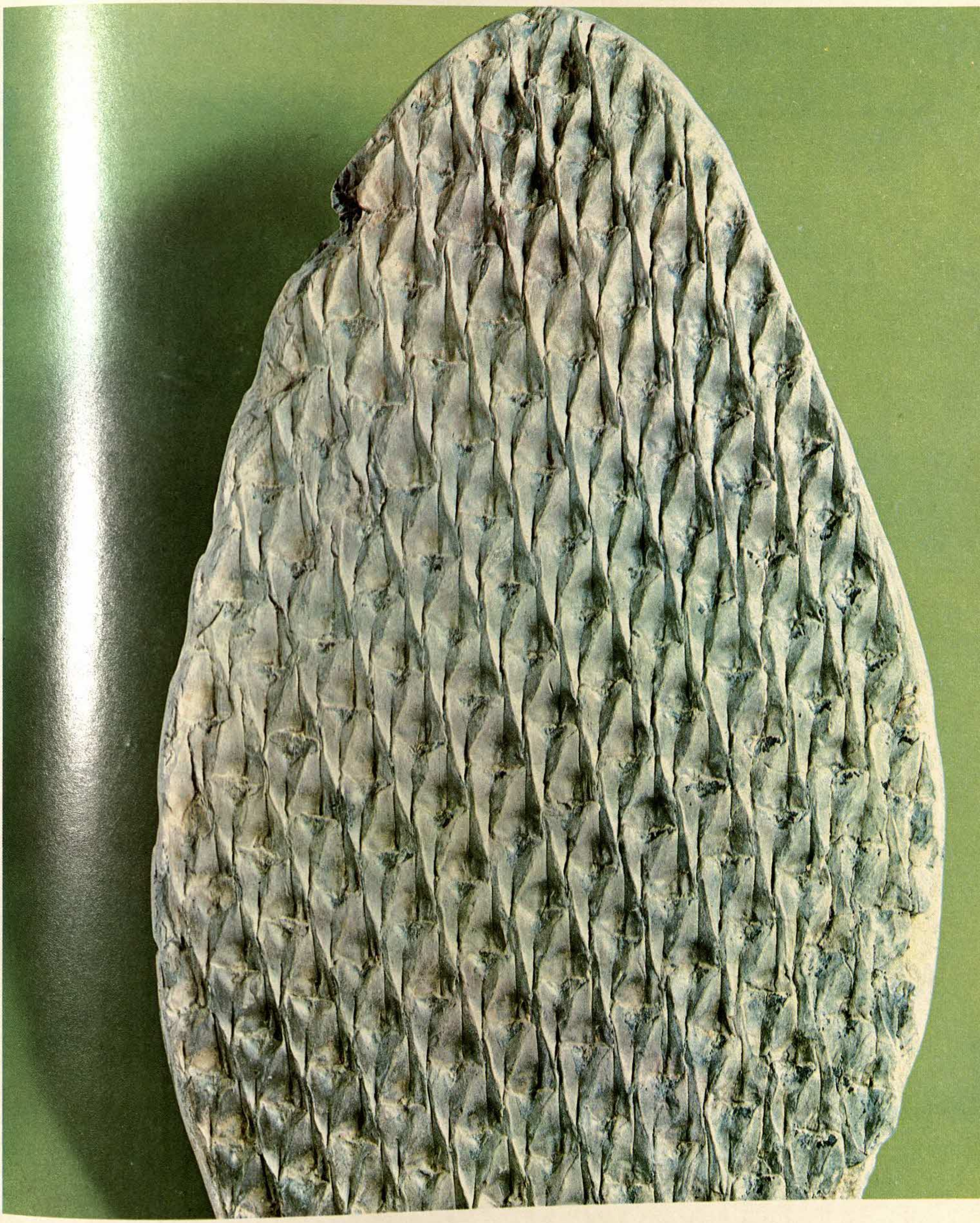
The macroscopic dimensions of the fossil algae found occasionally in Late Precambrian strata, as well as the occurrence of certain types of sedimentary rock among Late Precambrian formations, encourage the belief that in Late Precambrian times floating plants or phytoplankton had already spread throughout all the oceans. In addition to the few identifiable fossils of blue-green algae, fungi, seaweeds, and sponges that do occur in Late Precambrian rocks, there are occasional lumps of organic substances that were produced by the bacterial decomposition of the remains of organisms, and that, in some cases, may still resemble the actual life-form. Other Late Precambrian fossils are the remains of incompletely identified plant life in coal deposits whose thicknesses may be measured in meters.

The remarkable scarcity of fossils in Late Precambrian rocks, despite the fact that life at the time is believed to have existed in abundance and in many macroscopic forms, is commonly attributed to the fact that the various macroscopic forms of Late Precambrian life possessed neither internal nor external hard skeletons capable of being preserved or of leaving their imprint in the rock after the soft parts of the dead organism had decayed.



LATE PRECAMBRIAN LANDSCAPE—What is still primarily a marine landscape shows some of the more characteristic algae and pluricellular organisms of the time. The peculiar color of the water is due to plankton. The sands of the sea bottom are covered by many species of green algae. The land, however, is still barren, and the landscape above sea level alternates between coarse sedimentary plains and jutting mountains whose slopes are draped with majestic glaciers.

THE PALEOZOIC ERA | from the Cambrian through the Permian periods



THE PLANT EXPLOSION—One characteristic of the Paleozoic era was the evolutionary explosion of the plant and animal life that had occupied the seas during the preceding (Precambrian) era. During the Paleozoic, plants invaded the landmasses and, favored by a tropical climate, covered them with dense growth. Some plants grew to gigantic dimensions, and their accumulation led to the formation of extremely thick layers of coal on all the continents. Illustration 1 (preceding page) shows a fossil fragment of the bark of *Lepidodendron veltheimi*.

The Paleozoic era was once known as the Primary era, because it was believed that primordial life dated from this remote time in the Earth's history. However, it is now known that both the biological and geological phenomena characterizing this era were highly evolved.

Up until a few decades ago it was thought that life first appeared on Earth shortly after the beginning of the Paleozoic era—not long after the Earth's crust cooled. Advanced geological and paleontological studies have now proved beyond question, however, that living organisms existed on the Earth during an earlier time. Geologically, discoveries have been made of rocks that were consolidated about four billion years ago, indicating that the Earth's crust had solidified by then and that geologic forms of the kinds still observable today had already begun to exist. Biologically, fairly complex flora and fauna, composed of both unicellular and multicellular organisms and dating from Precambrian time, have been discovered. In addition, a fossil alga, possessing highly evolved characteristics and going back in time more than a billion years, has been located. Recently, discoveries have been made of traces of organic substances of biological origin that date from a time even more remote than late Precambrian time. In fact, it may now be affirmed that life was present on the Earth more than two billion years ago.

It is likely that in the future more data concerning these earlier, truly primordial eras will become available and that it will then be possible to subdivide the eras into periods, as has been done with more recent eras. For now, at least, it is possible to conclude that the Paleozoic era, like all subsequent eras, was a time of transition. Rocks from the Paleozoic are the earliest ones in which considerable quantities of animal fossils can be found.

CHARACTERISTICS OF THE PALEOZOIC ERA

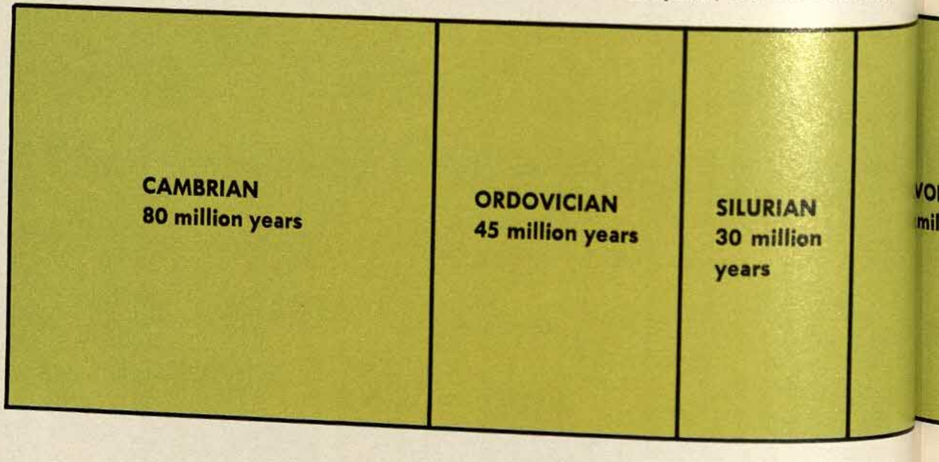
One important characteristic of the Paleozoic era, in terms of geological phenomena, and in contrast with the Precambrian, is the preservation of signs of the ebbs and flows of the seas—perhaps the most important phenomena geologists can investigate. From these signs, the paleogeography of the Paleozoic era can be reconstructed—an impossible task for preceding eras. This means that the outlines of the continents can be mapped with a certain precision. Moreover, the evolutionary history of the exposed lands can be deduced from such evidence.

Geologists have discovered traces of numerous important marine floods and of enormous orogenic phases that led to the formation of mountain chains. Some of the mountains, such as the Appalachians in the eastern United States, which were formed during the Permian period, still exist today, although they have been greatly diminished by constant erosion. Geologists have also discovered evidence of an important eruptive phase that was associated with the orogeny.

The biological world, no less than the physical Earth, underwent an extremely rapid evolution. In the Precambrian era life underwent profound changes. Multicellular organisms evolved from unicellular organisms; extremely simple systems became increasingly complex as organisms adapted themselves to survival in every type of marine environment. It is almost impossible to retrace the evolution of life in its very early stages, except in a theoretical way; however, the abundance of fossils from the Paleozoic, their perfect preservation, and

SUBDIVISIONS OF THE PALEOZOIC ERA—The Paleozoic era lasted for about 335 million years, from about 560 million years ago (the end of the Precambrian) until about 225 million years ago (the beginning of the Mesozoic era). The Paleozoic has been subdivided into seven periods, as shown in the illustration: Cambrian, Ordovician, Silurian, Devonian, Mississippian, Pennsylvanian, and Permian. In another system of classification, the Mississippian and Pennsylvanian periods are combined as one period, the Carboniferous.

The Cambrian period lasted about 80 million years; the Ordovician, about 45 million years; the Silurian about 30 million years; the Devonian, about 65 million years; the Mississippian, about 40 million years; the Pennsylvanian, about 40 million years; and the Permian,



their sizes make it possible to individualize the phases of biological evolution during this era.

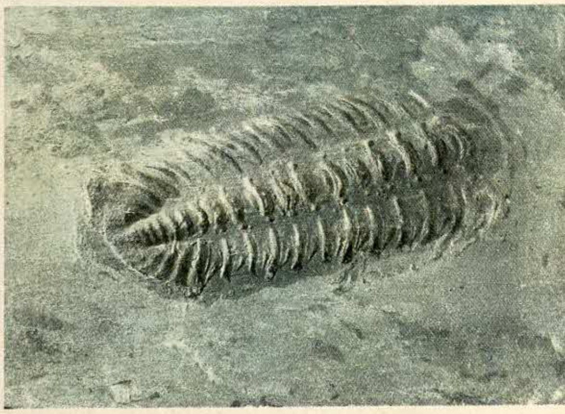
The number of large animals increased considerably during the Paleozoic. Chordates and vertebrates appeared, pulmonary respiration began, and life began to dominate the land. Insects appeared toward the end of the era, and there was a general tendency toward homoiothermy; that is, the body temperature of an organism's body tended to become independent of the temperature of the environment. These changes provided the first indications of the evolution toward mammalian forms.

The Paleozoic era was characterized by yet another phenomenon of extreme importance: the land was invaded by plants, which dominated the world scene for about 200 million years. Later on, the luxuriant growth of the Paleozoic (including the flora of the Pennsylvanian and Permian periods) waned somewhat, and in the following era (the Mesozoic), animal life came to dominate the globe both on land and in the sea.

PALEOZOIC CLIMATES

For the most part, the climate of the Paleozoic era seems to have been warm; however, there were many local and temporary differences. The Permian period, in particular, was marked by great climatic variations, ranging from warm, fairly wet climates, through semiarid and desert climates, to remarkably frigid climates. Indeed, there is evidence of widespread and repeated glaciation near the end of the era. When glaciers retreat, they leave behind morainic deposits that serve as evidence of the glaciation. From a study of these deposits, scientists can judge the contemporaneity of glacial deposits on every part of the Earth's land surface, and they can map the areas invaded by glaciers. An interesting fact emerges from these maps: South America, South Africa, India, and Australia have abundant morainic deposits dating from Permian times, while regions close to the present-day Arctic waters contain fossils of organisms that flourished in a tropical climate.

3



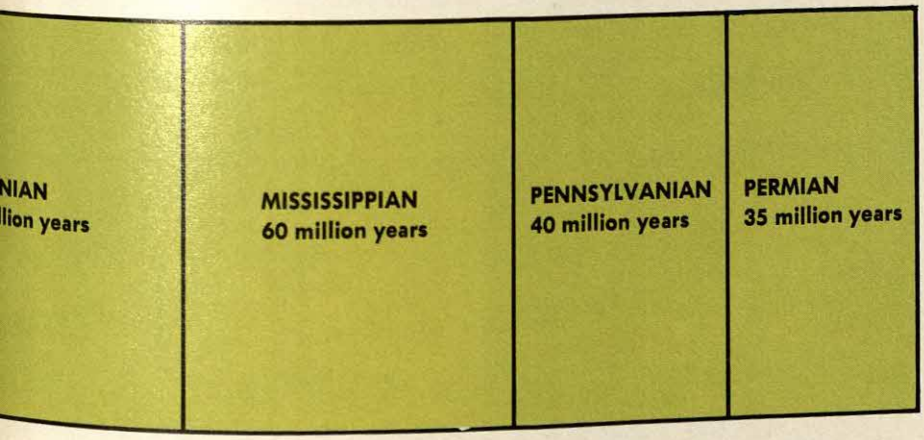
THE PROTOARTHROPODS—The beginning of the Paleozoic era was marked by the appearance of arthropods in primitive forms called protoarthropods. The trilobite shown here, with its body typically divided into three segments, is a good example of these new organisms. During the 355 million years of the Paleozoic era, innumerable examples of these aquatic animals existed; they varied in size from a few centimeters to many decimeters. The first trilobites were rigid organisms, but later species evolved that were able to roll themselves into balls. The trilobites disappeared mysteriously at the beginning of the Mesozoic era.

PALEOZOIC PRODUCTS

Important minerals date back to the Paleozoic era. Most of the leading coal fields of North America and Europe occur in Carboniferous strata. Petroleum is obtained from Carboniferous rocks only in the United States. Many metalliferous mineral deposits were formed from the mid-Carboniferous into the Permian, resulting largely from the action of mineral-bearing solutions derived from igneous intrusions. These include tin in Cornwall, England; silver and gold in France and Germany; copper and sulfur in Spain; and platinum in the Ural Mountains, which separate Europe from Asia. Similar deposits are almost unknown in the western hemisphere. Carboniferous rocks also contain minerals of later origin, such as the zinc and lead of Oklahoma and Kansas and the fluorites of Illinois and Kentucky.

about 35 million years.

Further subdivision of the periods into epochs (not shown) is approximate, inasmuch as the subdivisions have been determined by the relative thickness of the rock formations—a criterion that is somewhat lacking in precision. Nevertheless, subdivisions can be made on the basis of clearly defined breaks between the relative rock formations. Moreover, rocks that were formed during each of these epochs have been perfectly preserved, along with their fossils, justifying these fine subdivisions. It must be remembered that the acceleration of animal evolution during the Paleozoic makes it easier to characterize stratigraphically the various epochs. The names of the epochs are derived from the regions in which they were first identified and studied.



THE CAMBRIAN PERIOD | when seas invaded the land

← **THE CONSTRUCTING ALGAE** — Plant life in the Cambrian seas consisted largely of algae. Representatives of the Cyanophyta (blue-green algae) were widely distributed, and characteristically they favored the precipitation of the calcareous substances contained in seawater; hence they favored the sedimentation of large rock strata. From the Cambrian on, sedimentations caused by algae were typical in all seas. Not only did the algae give origin to certain rocks, but they left traces of their presence in those rocks. The illustration shows traces left in rock by representatives of the Schizophyta.

Hundreds of different kinds of trilobites lived in the seas during the Cambrian period, and they ranged in size from little more than 15 mm (about .6 in.) to 1 m (about 39 in.). Sponges and coelenterates were also present in Cambrian waters.

Beginning with the relatively recent time of the Paleozoic era, which commenced some 550 to 570 million years ago, scientists are able to reconstruct a number of facts concerning the Earth's history: the appearance of the landscape, the outlines of the continents, the flora and fauna, and the formation of mountain chains, vast plains, deserts, and glaciers. In a sense, the "written" history of the Earth begins with the Paleozoic era; this history, written in rock, can be deciphered by means of the sciences of paleontology, geology, and stratigraphy.

The Paleozoic era began with the Cambrian period, when innumerable living forms appeared to populate the seas. More than a thousand different kinds of organisms—including both plants and animals—have been described, indicating that living forms were abundant during this period and that a marked differentiation of species was already under way. During the latter part of the Precambrian era a large number of species must have existed, but few of their remains have been preserved; furthermore, those characteristics that are outstanding even in the fossils evolved very slowly. For this reason, an accurate evolutionary history cannot be established for the Precambrian era.

Beginning with the Cambrian period, the rate of evolution of living species accelerated. As long as organisms had unicellular or small, simple, multicellular forms, their primitive modes of food acquisition, locomotion, and adaptation to the environment were functional even under very diverse conditions. In such a situation mutations of an organism's characteristics were of little importance in determining the superiority of the mutated individual over others. However, when the organism became a complex machine that breathed, moved, and hunted food, by means of intricate mechanical or chemical systems, any change in those systems produced a notable variation in the conditions of adaptation and, therefore, also in the possibility of survival and dominance over other species. This diversification in the structures of living organisms, especially animals, favored geological reconstructions.

A living species that inhabited the Earth for a short time left fossils solely in a thin stratum of rock that was formed during the period of that species' existence. The presence of these fossils, there-

LANDS AND SEAS — The Cambrian period lasted for 70 to 90 million years. During this relatively long span of time, many important geological phenomena occurred, and the geography of the Earth was substantially altered.

This map shows the relative configurations and positions of the major landmasses and seas during the Early Cambrian epoch. South America had virtually the same outline it has today; however, during the Medial Cambrian epoch, it became joined to Africa by a land bridge; then during the latter part of the period, South America became grooved with marine basins communicating with the Pacific Ocean.

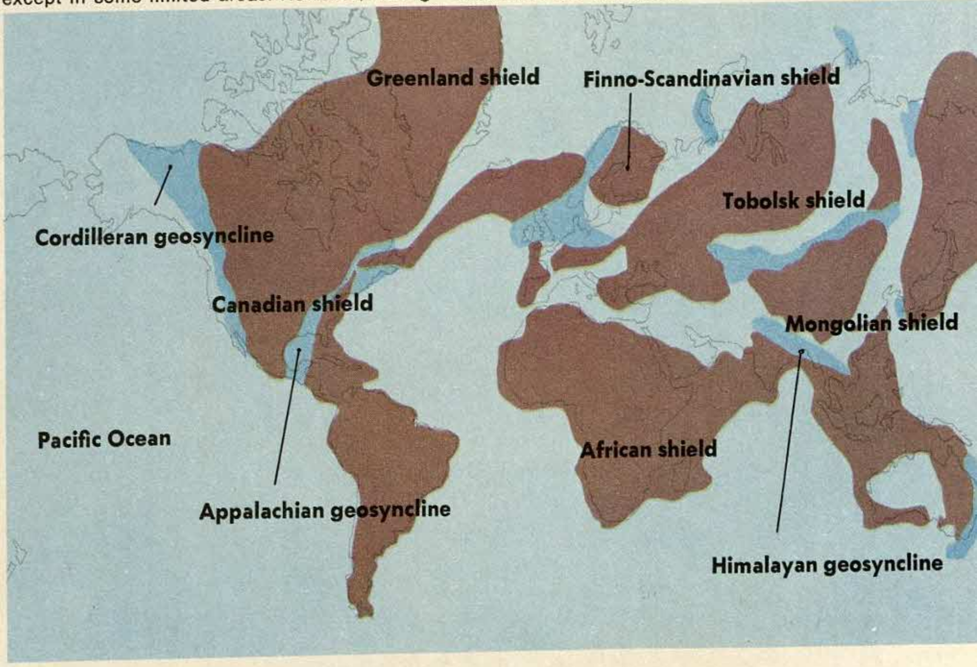
As the map shows, the North American continent consisted of a shield, a southward prolongation of the Greenland and Canadian shields. North America was bounded on the east and west by geosynclinal seas. The former, the sea occupying the Appalachian geosyncline, served to separate the North and South American continents; its name, of course, derives from the name of the mountain chain that arose there toward the end of the Paleozoic era. By the end of the Cambrian, these two geosynclinal seas had reached their greatest extension, and the North American continent was broken up into an archipelago of islands rising out of the seas.

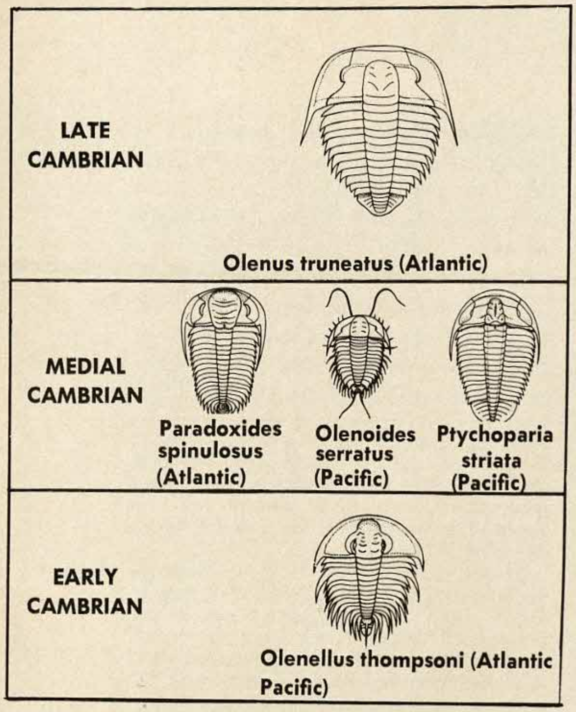
Throughout the entire history of the Earth, the Canadian shield was never submerged, except in some limited areas. However, during the Medial Cambrian epoch, a basin developed to separate the Greenland and Canadian shields. In the Late Cambrian epoch, the Greenland and Canadian shields were reunited, and the landmass extended as far as the coast of Norway.

Europe was almost totally submerged throughout the Early and Medial Cambrian epochs—with the exception of the Finno-Scandinavian shield. By the end of the period, however, Europe had emerged completely and was connected with Africa, Arabia, India, the Southeast Asian continent, and Australia.

The sea that ultimately would become the Mediterranean completely covered Italy during the Early and Medial Cambrian epochs and extended through what is now the Middle East into the heart of Asia. During the Late Cambrian, when Europe was joined to Africa and other landforms in the south and east, the region of the present Mediterranean was emerged, but the sea (known as the Tethys) still extended deep into Asia.

Asia itself was broken up into innumerable islands by geosynclinal seas; one of them extended as far as the region where the Himalayan chain would rise in the course of time. Australia was connected with Indonesia, India, and Africa, and these lands were not separated from one another until much later. Throughout the Cambrian, a large basin served to divide Australia into two parts.




LATE CAMBRIAN
Olenus truneatus (Atlantic)
MEDIAL CAMBRIAN
Paradoxides spinulosus (Atlantic)
Olenoides serratus (Pacific)
Ptychoparia striata (Pacific)
EARLY CAMBRIAN
Olenellus thompsoni (Atlantic Pacific)

SUBDIVISION OF THE CAMBRIAN PERIOD—The Cambrian can be divided into three epochs, each characterized by a different trilobite fauna. The most ancient part of the period, known as the Early Cambrian epoch, was characterized by *Olenellus,* which was found in both Atlantic and Pacific regions, *Wanneria, Holmia, Callavia,* and other genera. The next epoch, designated the Medial Cambrian, was characterized by *Paradoxides* in the Atlantic and by *Olenoides* and *Ptychoparia* in the Pacific, as well as by other genera of trilobites. The most recent part of the period, the Late Cambrian epoch, was characterized by *Olenus* in the Atlantic and *Dikelocephalus* in the Pacific, and by other important types. Altogether, about 1,500 different genera of trilobites from Cambrian times have been identified.

Despite the variations in the continental coastlines, which were indicative of the movements of the continental mass, the Cambrian was a period of orogenic and magmatic calm. Life had not yet invaded the emerged lands, and the agents of erosion, uninhibited by vegetation, acted freely, as in leveling the Huronian mountains, which had arisen during the Precambrian era.

As a further consequence of the rapid erosion during this period, sedimentation also occurred with notable speed. The total thickness of the Cambrian deposits is about 8,000 m (over 26,000 ft).

fore, is a certain indication of relative age. Fossils that permit such relative dating are called guide or index fossils. From the time of the Cambrian period onward, almost every epoch has left some organic remains that serve as guide fossils.

In the Cambrian, the trilobites appeared and evolved rapidly, and the period can be divided into three parts (Early, Middle, and Late Cambrian epochs), according to the species of trilobites that were dominant in each epoch. The abundance of fossil remains permits relative dating and temporal subdivision of the events that occurred during this period. From this time on, therefore, the boundaries of the seas and continents can be traced.

During the preceding era, the seas may have invaded the continents and withdrawn any number of times, but the absence of fossils makes it difficult to establish how and when these events may have occurred. However, one important fact must be considered: the great continental masses have remained the same throughout geological history. Sometimes they have been submerged and at other times they have been folded to form important mountain chains; but never has a new continental landform risen up in the center of the Pacific Ocean, even for a brief time.

From the physical point of view, the invading or transgressing seas must be distinguished into two types: those originating from a change of level of the continental mass (geosynclinal seas), and those originating from a change in the overall level of the seas themselves (epicontinental seas).

Geosynclinal seas result from the downward sloping or curving of the continental mass, which leads to the formation of a cavity that later becomes filled with seawater. Such tracts of sea, which have now disappeared, also are called subsident basins. Through the course of geological time, many geosynclinal seas became filled with thousands of feet of sediments that, following consolidation, were raised up and folded to form mountain chains.

FLORA AND FAUNA OF THE CAMBRIAN—This illustration of a section of the sea during Cambrian times shows some of the predominant organisms of the period; blue algae, brachiopods, and trilobites (enlarged) thrived in the sea, but the land was barren.

THE SPREAD OF THE INVERTEBRATES

faunal development during the Cambrian

1

← **AGE OF THE TRILOBITE**—The Paleozoic era has been described as the Age of the Trilobites. These primitive arthropods were widely distributed throughout the entire era and then became extinct. During the Cambrian period, the trilobites developed from very small animals into much larger ones. In subsequent epochs, some kinds of trilobites developed the ability to roll themselves into balls. Other types evolved slender, hydrodynamic forms that enabled them to move through the water rapidly. Illustration 1 shows a very well-preserved fossil of a trilobite about 6 cm (about 2.4 in.) long. It was discovered in Cambrian rocks near Prague, Czechoslovakia.

Little is known of the fauna and flora of the Cambrian period. The flora, which was completely marine, has been studied only in part. The fauna, which was also marine, was scarce and primitive. In comparison with the large and profuse saurians and mammals of later periods, Cambrian animals were modest in both size and number. Scientists estimate that only about 1,500 species were in existence, and this figure accounts for species that may never be known because their fossil remains may never be discovered or because they left no fossil remains.

The Lower Cambrian was marked by the appearance of several groups of invertebrates, including the echinoderms, trilobites, crustaceans, snails, and sponges. Forms that preceded the chordates may also have been present.

The Middle Cambrian witnessed a specialization of species. For example, the trilobites, which are considered as the true guide fossils for this period and the whole of the Paleozoic era, have been subdivided into different types according to the different sea zones (Atlantic, Pacific, and Arctic) and different epochs. The brachiopods and echinoderms, secondary guide fossils, have been subdivided similarly. Finally, in the Upper Cambrian, the amount of lime in shells increased and the number of snails and brachiopods expanded greatly.

All forms of life were aquatic. The land was barren; erosion was furiously leveling the continents. Interestingly, however, living organisms were no longer evenly distributed through the seas; several species began to live in shallow waters along the coasts. This was the first step in the evolutionary process by which life would eventually conquer the land. Although land animals are unknown for the Cambrian period, at least three-quarters of all animal evolution had already taken place.

A PRIMITIVE FAUNA

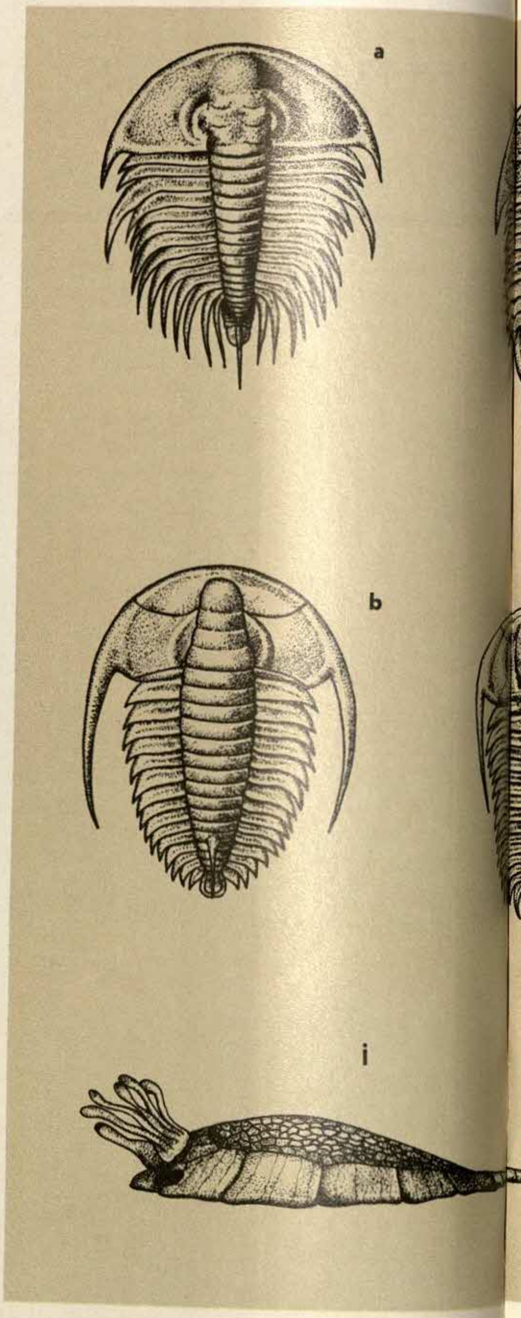
In comparison with Precambrian fauna, Cambrian fauna was highly evolved. Nevertheless, it was still quite primitive in comparison with present-day forms of life. For the most part, Cambrian animals were stationary, plankton-feeding organisms. Most had no organs for fast movement or hunting. They lived independently—that is, the presence of one animal did not result in the destruction of another. There was enough food for all, because the waters of the sea moved slowly, distributing the food evenly. These organisms had digestive apparatuses enclosed in protective integuments. Some of the animals had primitive sense organs, but most of them were completely isolated from sensations. Locomotion was barely developed in most animals; even the simple motion of sliding over the muddy sea floor required rather highly developed organs of locomotion.

Many kinds of Cambrian animals—the protozoans, coelenterates, ctenophores, worms, and many primitive arthropods—had no hard parts at all; and though the bodies of some Cambrian jellyfishes, worms, and crustaceans were sometimes preserved, such fossils are rare. An example of such preservation, brought about under exceptionally favorable conditions, occurs in the Middle Cambrian Burgess shale of the Canadian Rockies in British Columbia. On the bedding planes of the fine black shale, the soft bodies of many otherwise unknown invertebrate animals and pieces of soft seaweeds were impressed to form shiny carbon films that have retained perfectly the original structures.

INDEX FOSSILS

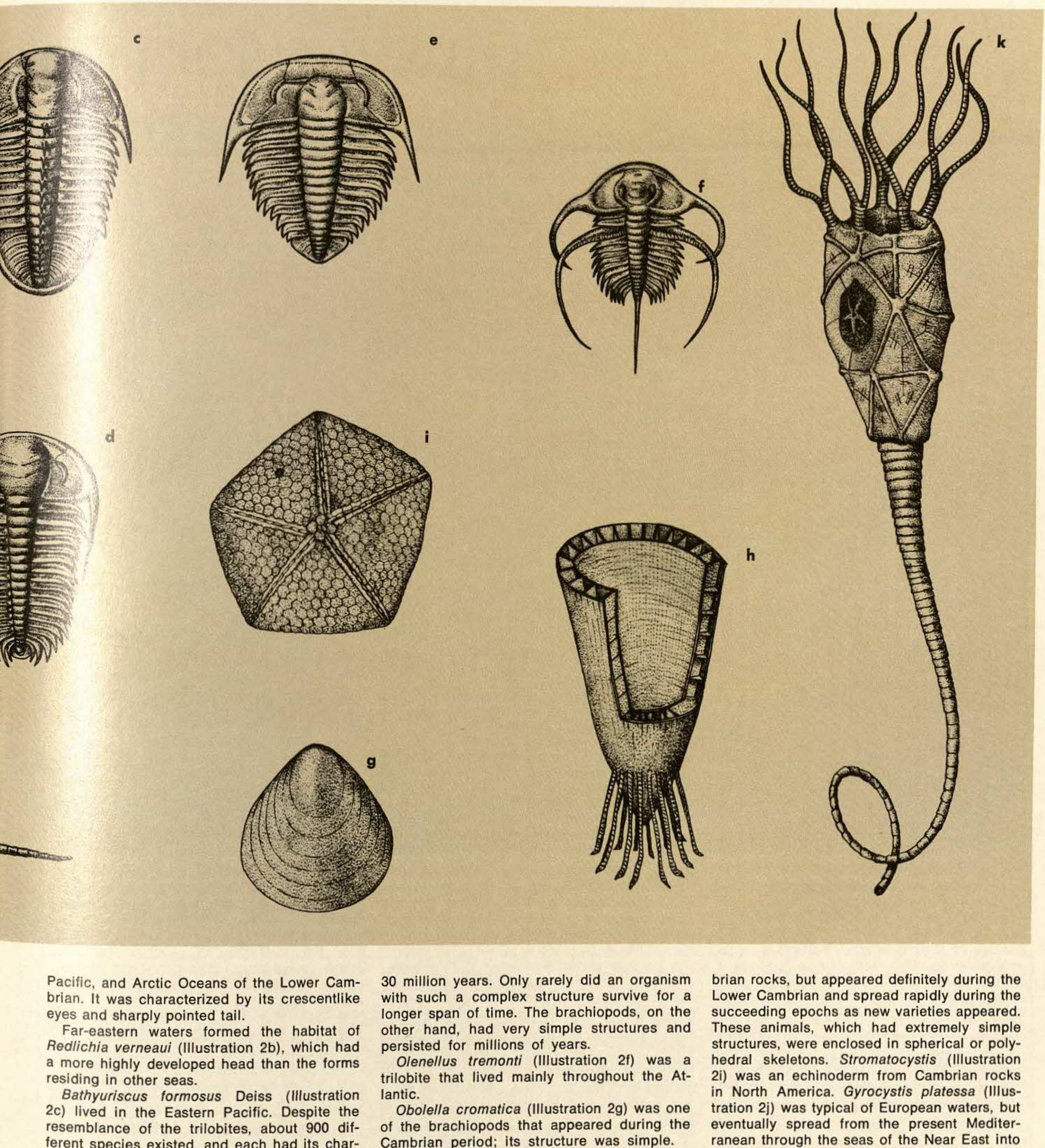
Trilobites, as has been mentioned, are the best and most abundant of Cambrian

2



CAMBRIAN FAUNA—The Cambrian period was characterized by the appearance of various groups of invertebrates. The structures of some of the most important examples are shown.

The trilobites were the most common animals of the Cambrian period. These primitive arthropods had rigid chitinous integuments that were articulated and compact. The body of *Olenellus thompsoni* (Illustration 2a) of the Lower Cambrian was divided into segments that tapered downward. Each segment was divided into longitudinally closely jointed parts. The joint between two segments was a chitinous membrane similar to the shell, but thinner and more flexible. This flexibility enabled the trilobite to bend. In the Middle and Upper Cambrian, the flexibility became more pronounced, enabling the animal to curl itself into a ball. However, all the trilobites shown here were semirigid. *Olenellus* lived in the Atlantic,



Pacific, and Arctic Oceans of the Lower Cambrian. It was characterized by its crescentlike eyes and sharply pointed tail.

Far-eastern waters formed the habitat of *Redlichia verneaui* (Illustration 2b), which had a more highly developed head than the forms residing in other seas.

Bathyuriscus formosus Deiss (Illustration 2c) lived in the Eastern Pacific. Despite the resemblance of the trilobites, about 900 different species existed, and each had its characteristic form and physiology.

Paradoxides (Illustration 2d) was widely distributed throughout the Atlantic Ocean during the Middle Cambrian epoch. Many varieties of *Paradoxides* existed; all appeared and disappeared within the 30-million-year span of the Middle Cambrian.

Olenus truncatus (Illustration 2e) was a trilobite of the Upper Cambrian. Each species was short-lived, usually enduring for about 30 million years. Only rarely did an organism with such a complex structure survive for a longer span of time. The brachiopods, on the other hand, had very simple structures and persisted for millions of years.

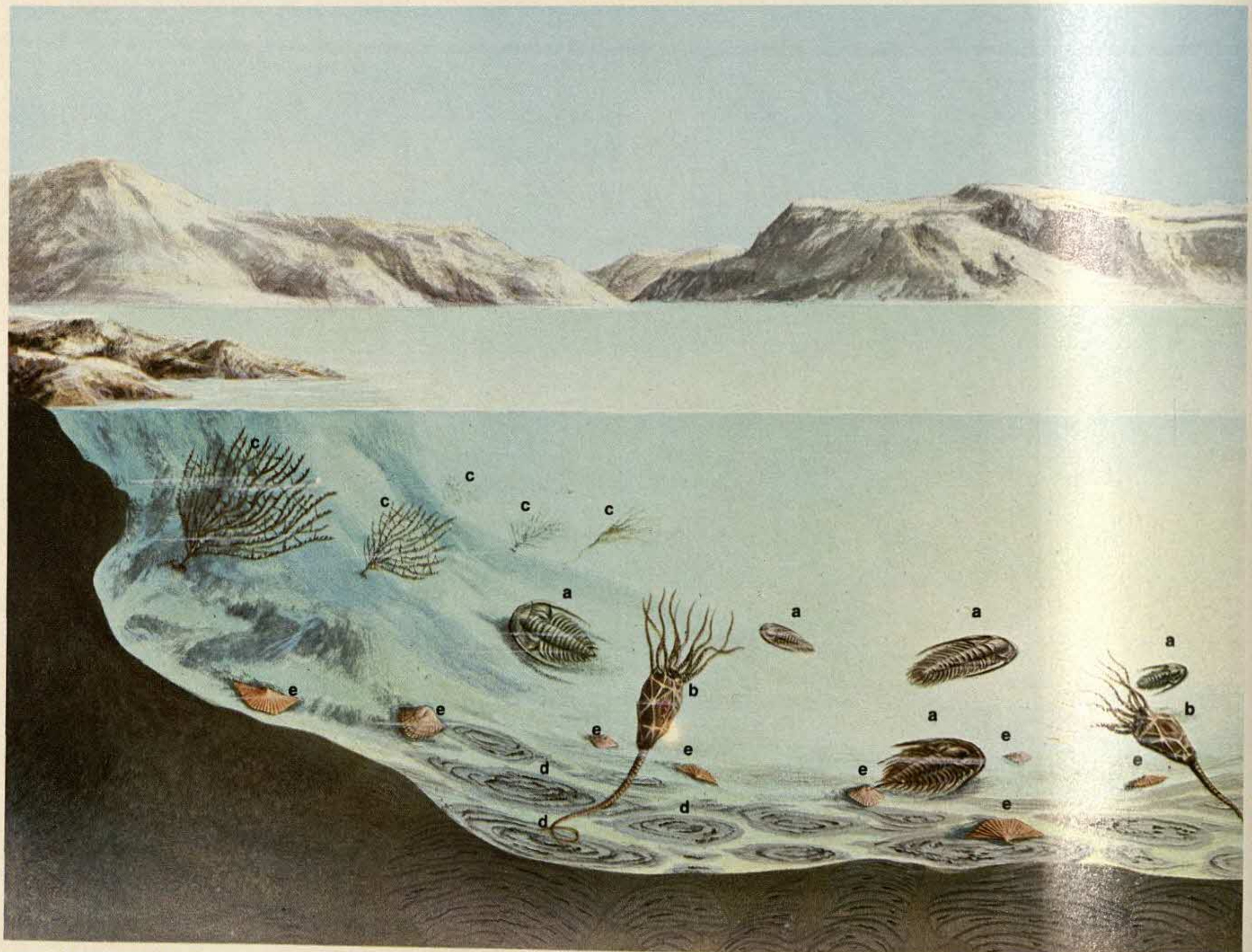
Olenellus tremonti (Illustration 2f) was a trilobite that lived mainly throughout the Atlantic.

Obolella cromatica (Illustration 2g) was one of the brachiopods that appeared during the Cambrian period; its structure was simple.

Archeocyathans—organisms somewhat resembling sponges, but constituting a separate and totally extinct phylum—underwent a rapid evolution. Specimens of these organisms are used as guide fossils to date Cambrian rocks. *Coscinocyatus* (Illustration 2h) lived during the Middle Cambrian. This fossil is a reliable indicator of the age of the rocks in which it is found.

Echinoderms left vague traces in Precambrian rocks, but appeared definitely during the Lower Cambrian and spread rapidly during the succeeding epochs as new varieties appeared. These animals, which had extremely simple structures, were enclosed in spherical or polyhedral skeletons. *Stromatocystis* (Illustration 2i) was an echinoderm from Cambrian rocks in North America. *Gyrocystis platessa* (Illustration 2j) was typical of European waters, but eventually spread from the present Mediterranean through the seas of the Near East into Asiatic waters.

Macrocystella (Illustration 2k), an echinoderm of the class Cystoidea, appeared during the Upper Cambrian. The cystoids were immobile, fixed fauna—that is, they were firmly attached to the seabed. This form lived for about 150 million years, just a part of the Paleozoic era.



THE CAMBRIAN LANDSCAPE—This illustration is a cross section of the Cambrian waters, together with a fragment of the heavily eroded land. The common trilobites **a** skimmed the floor of the sea, while echinoderms **b** and colonies of graptolites **c** were attached to the underwater coastal rocks. Large extensions of cyanophytes **d** covered the bottom to great depths. Hardy species of plankton appeared in all the seas in great abundance. The presence of these organisms and certain sponges suggests that a uniformly hot climate prevailed. Brachiopods ● also lived on the sea floor.

The illustration is not totally accurate in that the living organisms of the Cambrian period did not live close together in the same waters. The purpose of the illustration is to provide a certain number of examples of Cambrian fauna in order to show the difference between this period and the preceding one.

The graptolites, which also appeared during the Cambrian period, lived in colonies even though the animals themselves were extremely primitive. They were covered with a chitinous substance and had branched colonies. Scientists have classified graptolites into two groups, according to their formations. Graptolites of the species *Dictyonema flabelliforme* **c** were particularly abundant.

index or guide fossils; and they are customarily used to distinguish the faunal zones of the period. There are about 1,500 described genera of Cambrian trilobites. They were more numerous and varied in the Cambrian seas than in the seas of any other period. About 75 percent of the fossils found in Cambrian rocks are the remains of trilobites; they represent the numerous molts as well as the actual dead animal. About 20 percent of the Cambrian fossils are the shells of brachiopods, and the remaining 5 percent includes all the other animals that are represented in the ancient rocks.

THE ORDOVICIAN AND SILURIAN PERIODS

a 75-million-year span of Earth history

Geologists often experience great difficulty in determining when one geologic period ended and another began. Frequently, the epochs within a period have been determined by the number of times during the period that certain areas were submerged and other areas emerged. Geologists find it relatively easy to make subdivisions in cases where a vast land region was suddenly—insofar as a geological event can be said to happen suddenly—and completely covered with water, or where a vast land region suddenly emerged from the sea. Epochs may also be determined by the sudden appearance or disappearance of animals or plants that evolved rapidly.

Geologists of many lands have studied the rocks of the Earth and the fossils enclosed in various rock strata; on the basis of their discoveries, they have divided Earth history into eras, periods, epochs, and ages. Unfortunately, different classification systems have been developed, primarily because the geological and biological events occurring during a particular time in Earth history differed from one locality to another. Consequently, some confusion exists concerning the labeling of periods, epochs, and ages.

In Europe, for example, the period of time immediately following the Cambrian and immediately preceding the Devonian is called the Silurian period. In the United States, on the other hand, this 75-million-year span is considered as encompassing two distinct periods, the Ordovician and the Silurian. The Ordovician began at the end of the Cambrian, about 480 million years ago, and lasted for approximately 45 million years. The Silurian, then, began about 435 million years ago and lasted about 30 million years, or until about 405 million years ago. The epochs into which these two periods have been divided vary from continent to continent.

During the Ordovician and Silurian periods, the land consisted of three main divisions: a North Atlantic continent, an Asiatic continent, and an Austral-Equatorial continent. In shape and location, these landforms bore very little resemblance to the present-day continents.

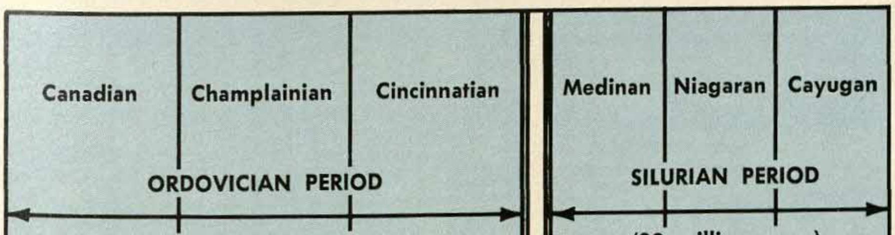
The primitive landmasses were subjected to continual changes: changes in latitude and longitude; changes in elevation that resulted in the submergence of some areas and the emergence of other areas; transformations produced by mountain-building activities and erosive processes; and alterations in the Earth's crust and surface features brought about by movements of magma from the depths. With the passage of time—hundreds of millions of years—the landforms evolved their present contours and reached their present positions.

The Ordovician period was characterized by one orogenic episode, the uplifting of the Taconian Mountains in the eastern part of North America. These mountains were eroded in subsequent periods, and the products of erosion eventually were incorporated into the rocks that formed the Appalachian Mountains in the latter part of the Paleozoic era.

Near the end of the Silurian, orogenesis of major importance occurred in the British Isles, Norway, Spitzbergen, and the northern end of Greenland. This period of mountain building is known as the Caledonian orogenesis or—because the activity was of such widespread significance—the Caledonian revolution.

The 75-million-year duration of the Ordovician and Silurian periods is a short span of time in comparison with the billion years of the Archean (early Precambrian) period. Nevertheless, life-forms made great advancements during these two periods. Little by little, living organisms became more numerous and more complex. Whereas the preponderance of life-forms of the Cambrian period had been unicellular, multicellular organisms became abundant during the Ordovician and Silurian periods. Animals evolved very rapidly, in fact, because the more complex organisms are, the more subject they are to mutation.

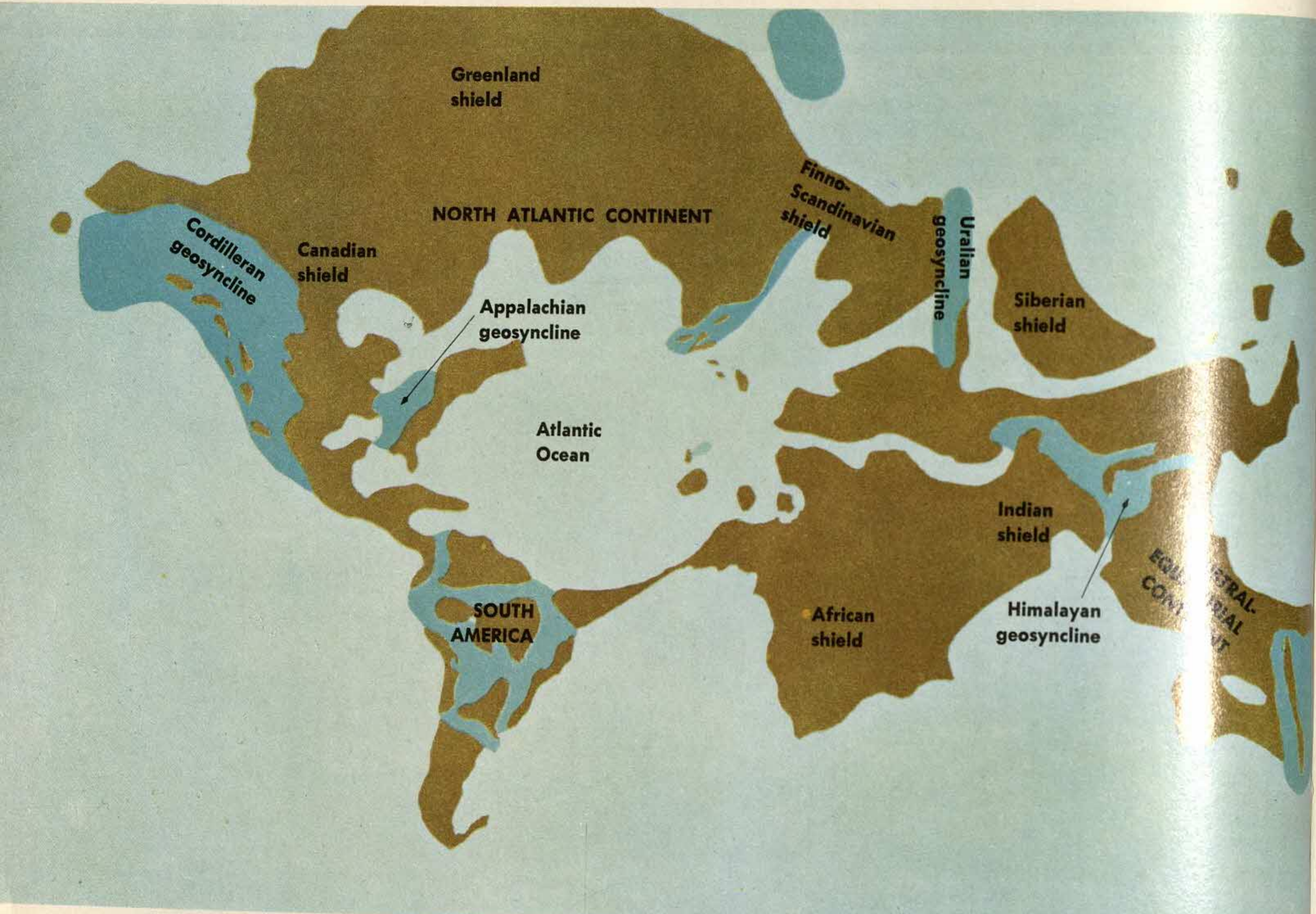
During the latter part of the Silurian, life-forms made their first tentative ex-



SUBDIVISIONS OF THE ORDOVICIAN AND SILURIAN PERIODS—The denominations of these two important periods have long been controversial. Some geologists consider the two periods as part of the Cambrian, while others believe the Ordovician and Silurian to be simply one long period. In North America, however, the periods are considered separate and distinct. American geologists ordinarily subdivide the Ordovician into three epochs: the Canadian or Lower Ordovician, the Champlainian or Middle Ordovician, and the Cincinnatian or Upper Ordovician. In some classification systems, what is here considered the Middle Ordovician is divided into two epochs known as the Chazyan and Mohawkian epochs.

The Silurian is also divided into three epochs: the Medinian or Lower Silurian, the Niagaran or Middle Silurian, and the Cayugan or Upper Silurian. European subdivisions are more detailed than the American.

cursions into land environments. Among the earliest terrestrial plants were the primitive fernlike pteridophytes. The first animals to adapt even partially to a terrestrial existence were shrimplike organisms, eurypterids, with two large claws and a tail similar to that of a scorpion. These animals were not completely independent of the aquatic environment. In subsequent periods, living organisms conquered the land and populated the various terrestrial environments.



CONTINENTS AND SEAS IN ORDOVICIAN AND SILURIAN TIMES—The terrestrial planisphere of the Ordovician and Silurian periods differs substantially from the planisphere of the Cambrian period and from that of the present day. Modern interpretations indicate that the Ordovician and Silurian were characterized by three important continents: the North Atlantic, the Asiatic, and the Austral-Equatorial.

The North Atlantic continent consisted of those terrestrial regions that today constitute the continent of North America, Greenland, Scandinavia, and the Russo-European continental shelf. This huge landmass probably was separated from the other land areas of the Northern Hemisphere and from the Asiatic continent by a slender inlet of the sea occupying the Uralian geosyncline. The Asiatic continent was furrowed with many seas, which at times were in close connection with, or proximity to, the Arctic Ocean. A huge oceanic inlet served to separate Africa and India from the northern parts of Europe.

The Atlantic Ocean was bounded on the north and south by land. On the north the ocean was closed off by the North Atlantic continent; on the south, it was probably limited by a land bridge joining South America with Africa. Scientists cannot say with certainty that the land bridge was as elongated as it appears in the map above; the continents may actually have been closer together during Ordovician and Silurian times than this map indicates, in which case a shorter land bridge would have sufficed to unite these landmasses in the Southern Hemisphere. The Austral-Equatorial continent was separated from the Afro-Indian landmass, at most, by a narrow arm of the sea.

South America was partly submersed and partly emerged. North America was subjected to extensive marine transgression, both in the Upper Ordovician and Middle Silurian epochs. By the Upper Silurian, however, the transgressing seas were greatly restricted, and most of North America had emerged. Throughout the two periods, the Rocky Mountains were nonexistent; where this chain now stands in majestic relief a great geosynclinal sea existed. Islands arose from this sea and volcanoes formed, probably as a result of the foundering and sinking of the geosyncline. Part of the Appalachian geosyncline was heaved up from the water, but this land remained separated from the rest of North America by an inlet of the sea.

FROM ONE CELL TO MANY CELLS

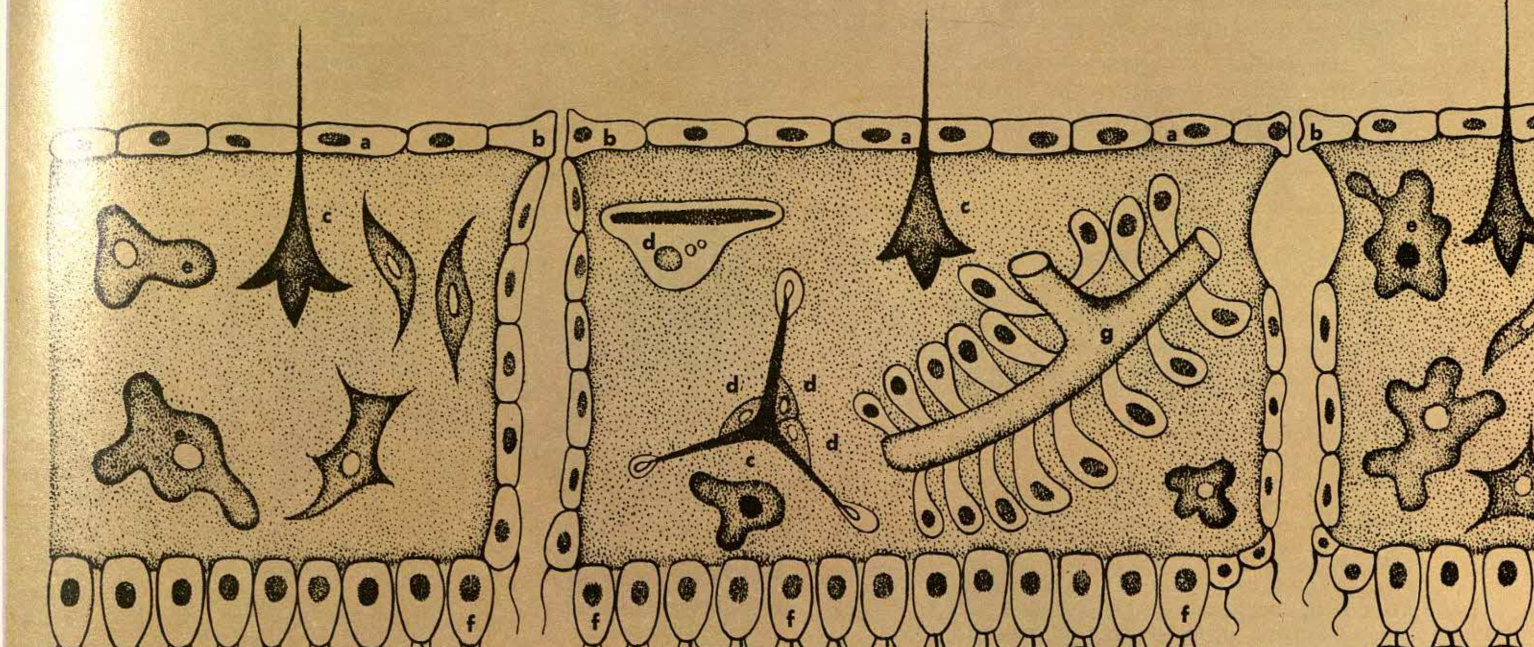
first steps in specialization

For some incompletely understood reason, the unicellular organism had a tendency to complicate its simple existence. Perhaps this tendency grew out of a need for an increase in size or the need for a more efficient structure. An increase in the size of the cell resulted in the multiplication of the number of nuclei in the cell; certain amoebas, for example, may have as many as 50 nuclei. On the other hand, the grouping together of cells into colonies provided for division of functions and greater efficiency; in such colonies, the cells were equal, but they began to specialize in different functions necessary for communal living.

The latter was the first step in the evolution from one cell to many cells. However, at this stage of development, the organisms were not really multicellular; they became so through the increasing specialization of the individual cells in the colonies. The individual cells began to lose their ability to live independently; therefore, in a manner of speaking, they were multicellular.

An example of this was the class Flagellatae—unicellular organisms united in a colony in which the members already showed a distinct specialization and slight morphological differences. The differences among the cells became more pronounced as the need to find food and move freely increased or perhaps as the advantages of communal living became evident in terms of survival. In any event, the cells continued to differentiate and become increasingly more specialized. At this point in the evolutionary process, the cells constituted multicellular organisms. The anterior cells—the smallest ones—had long flagella that served to move the organism along with their whipping action. (In the case of the immobile sponge, movements of flagella served to generate

1 **THE STRUCTURE OF THE SPONGE**—This illustration shows that, even though the sponge is extremely primitive, it exhibits a notable differentiation of cells and specialization of functions. The outer surface of the sponge consists of rather flat cells **a** and contractile cells, the porocytes **b** that regulate the flow of water through the inhaling pores. Inside the cell are the spicules **c**, which are immersed in an intercellular substance; the scleroblasts **d**, which produce the spicules; the amoebocytes **e**, which carry food to the other cells; the choanocytes **f**, flagellate cells with transparent collars that circulate the water; and spongin fibers **g**.

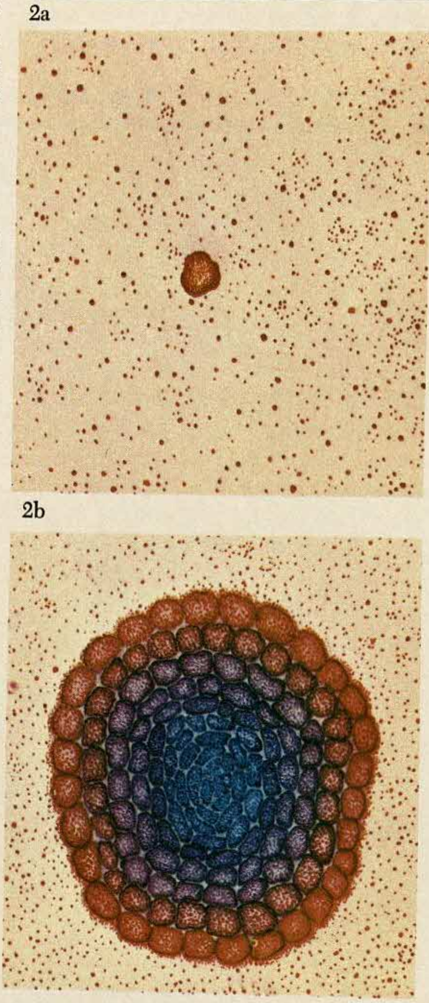


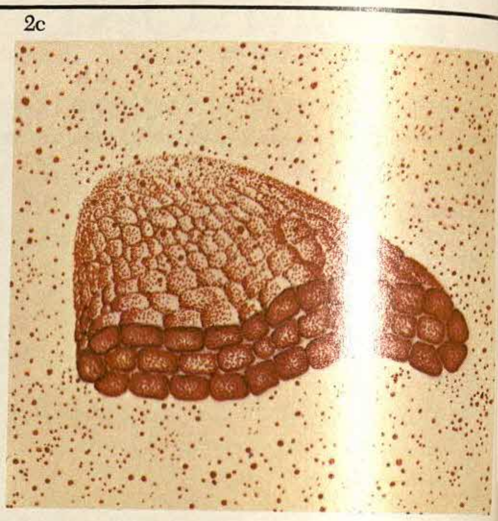
currents in the water, driving water into the body.) Other cells, called phagocytes, which were located along the underside of the organism, functioned as a kind of digestive system.

THE PHAGOCYTES

The phagocytes or phagocytic cells of a simple multicellular organism serve to satisfy the organism's nutritional needs in much the same way as an amoeba satisfies its food requirements—that is, by surrounding or enveloping food particles. In the case of the amoeba, which has no rigid cellular membrane, cytoplasmic extensions or pseudopodia gradually flow around a food particle and engulf it. The food is enclosed in a food vacuole that moves toward the center of the amoeba, where the food is digested by the action of enzymes.

The development of phagocytes and the process of phagocytosis in multicellular organisms constituted another high-water mark in the story of life. The organism did not have to wait passively for nutritionally useful substances to penetrate it; rather the organism could actively seek and ingest food substances, breaking them down and eliminating the indigestible parts. Some organisms advanced further, enfolding the outer phagocytes within a cavity. In time, of course, much more intricate digestive

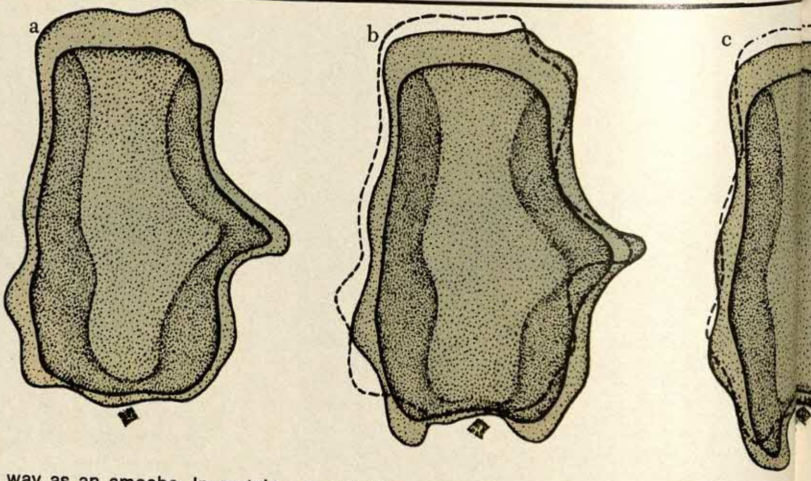




UNICELLULAR AND MULTICELLULAR ORGANISMS—In the multicellular organism several cells specialized in such a way as to carry out a specific function more efficiently or more effectively than is possible for individual cells. The multicellular organism thereby could face new situations and new environments. For example, several of its cells began to produce a hard substance that formed a rudimentary skeleton or an integument. The organism could then increase in size and use its integument to protect or defend itself against environmental hazards.

A unicellular organism must assimilate food from the surrounding water, usually by diffusion. Illustration 2a shows how food diffuses rapidly through the wall of the cell and is quickly metabolized. The smaller the organism, the larger the surface area of the body in relation to its volume. A unicellular organism with a volume of 1 cubic micron has a surface area

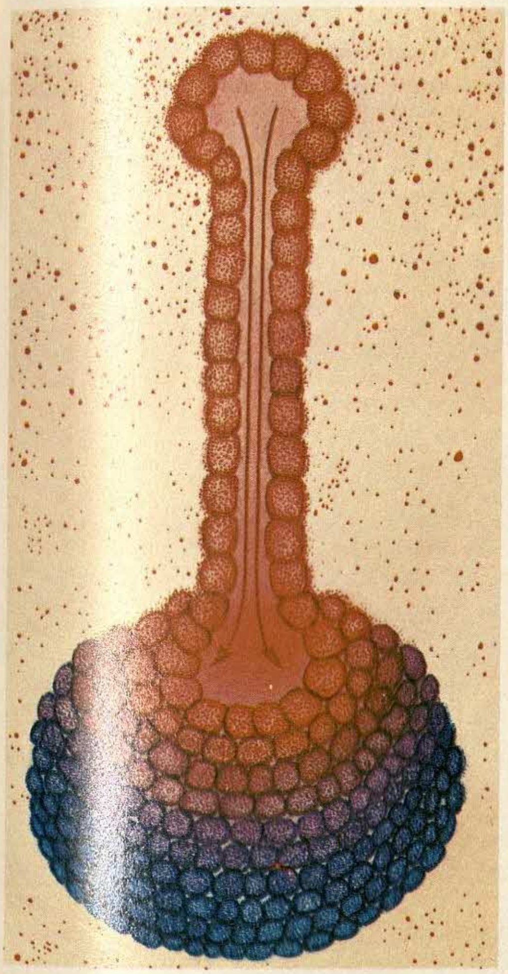
3



MOVEMENTS OF THE AMOEBA; PHAGOCYTES—The amoeba is a protozoan of microscopic dimensions (5 to 500 μm), which is distinguished by its system of locomotion. This single-celled organism, which lacks any rigid matter, is capable of changing its shape in any direction. It does this by forming extensions called pseudopodia, or false feet. A portion of the material in the cell flows outward in any direction, and other protoplasm in the cell flows into the vacated region. In this way, the amoeba moves along. This ability to change shape and move is utilized by the amoeba in satisfying its nutritional requirements. When the amoeba is near a food particle, it utilizes its pseudopods to surround and envelop the particle in a vacuole that is then pushed toward the center of the cell. Various steps in this process of food acquisition are shown in Illustrations 3a, 3b, 3c, 3d, and 3e.

Phagocytes, specialized cells of multicellular organisms, change shape and move in much the same way as an amoeba. In certain simple organisms, the phagocytes constitute a primitive nutritional or digestive system. In higher organisms, they serve other functions.

2d

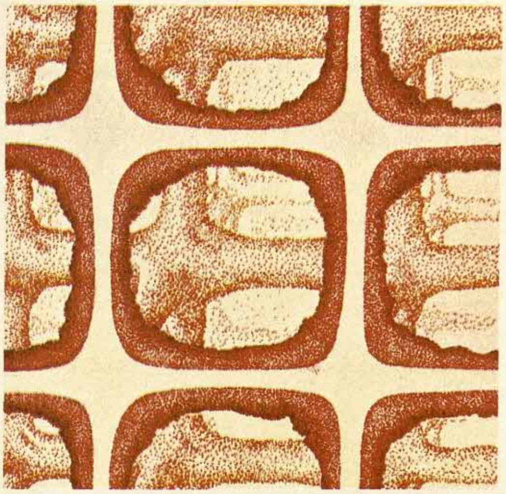


of 6 square microns; 100 billion of these organisms would be required to make a liter of living matter, but all of them together would have a surface area of 6,000 m². If they were put in water containing nutrients, in a very short time they would assimilate the food and eliminate the wastes. Unicellular organisms carry out these functions with lightning speed.

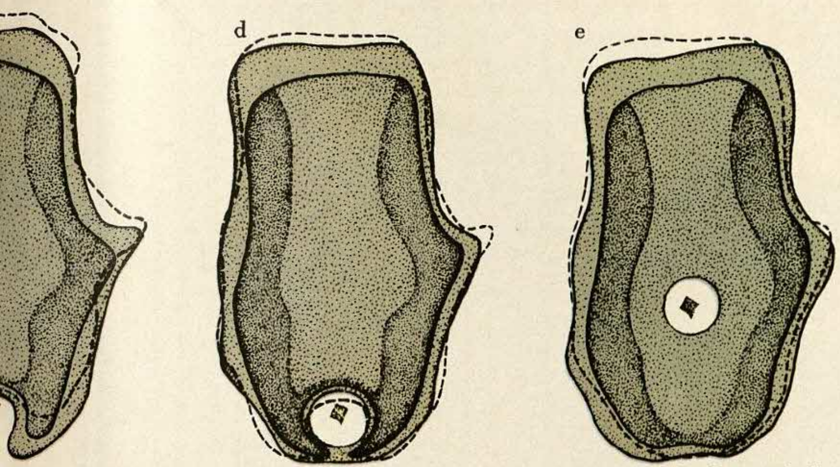
Illustration 2b shows how a simple multicellular organism feeds itself. The organism shown is actually a compact mass of cells. If it has a volume of one liter, it has a surface area of six square decimeters—as compared with the 6,000 m² surface area of a liter (100 billion) of the unicellular organisms mentioned in the preceding paragraph. In other words, if this organism were to acquire and assimilate as much food as the liter of unicellular organisms, it would have to do so through a much smaller surface. Food must enter the outer cells and diffuse through all parts of the organism in order to reach the center; this is a rather slow process.

In the early phases of evolution, the multicellular organisms that developed from unicellular organisms were simple and primitive. The cells that kept multiplying piled up one on the other and often caused the death of the organism. Only an organism with a system for metabolizing the food from the water survived. Illustration 2c shows such an organism. It had a large surface area, but was vulnerable because of its greater size. In a relatively short time, a new form evolved that overcame this difficulty. This new form had cells that were adapted to certain specialized functions, such as digestion and respiration. Illustration 2d represents a structure specialized for digestion. It had an appendage and a thin absorbent surface through which food was conducted (in a fluid) to the center of the body.

4



THE STRUCTURE OF THE SKELETON—The development of a skeletal structure was of monumental importance in organic evolution. Certain cells became specialized in producing and accumulating solid resistant matter inside the organism. This accumulation then formed a complex rigid structure that supported the organism. The skeleton of a sponge differs widely from the skeletons of highly developed vertebrates. It is a complex lattice of calcareous, siliceous, or corneous bars supporting the entire body of the organism. Its shape and structure are variable from one species to another. This illustration shows a typical skeletal structure, a lattice of small square links. The intersections of the bars, which are the rigid elements, are strengthened by the oblique bars, which make the structure resistant to the movements of the links. The rigid matter has a rough, uneven surface covered with tiny spines to which the walls of the cells attach.



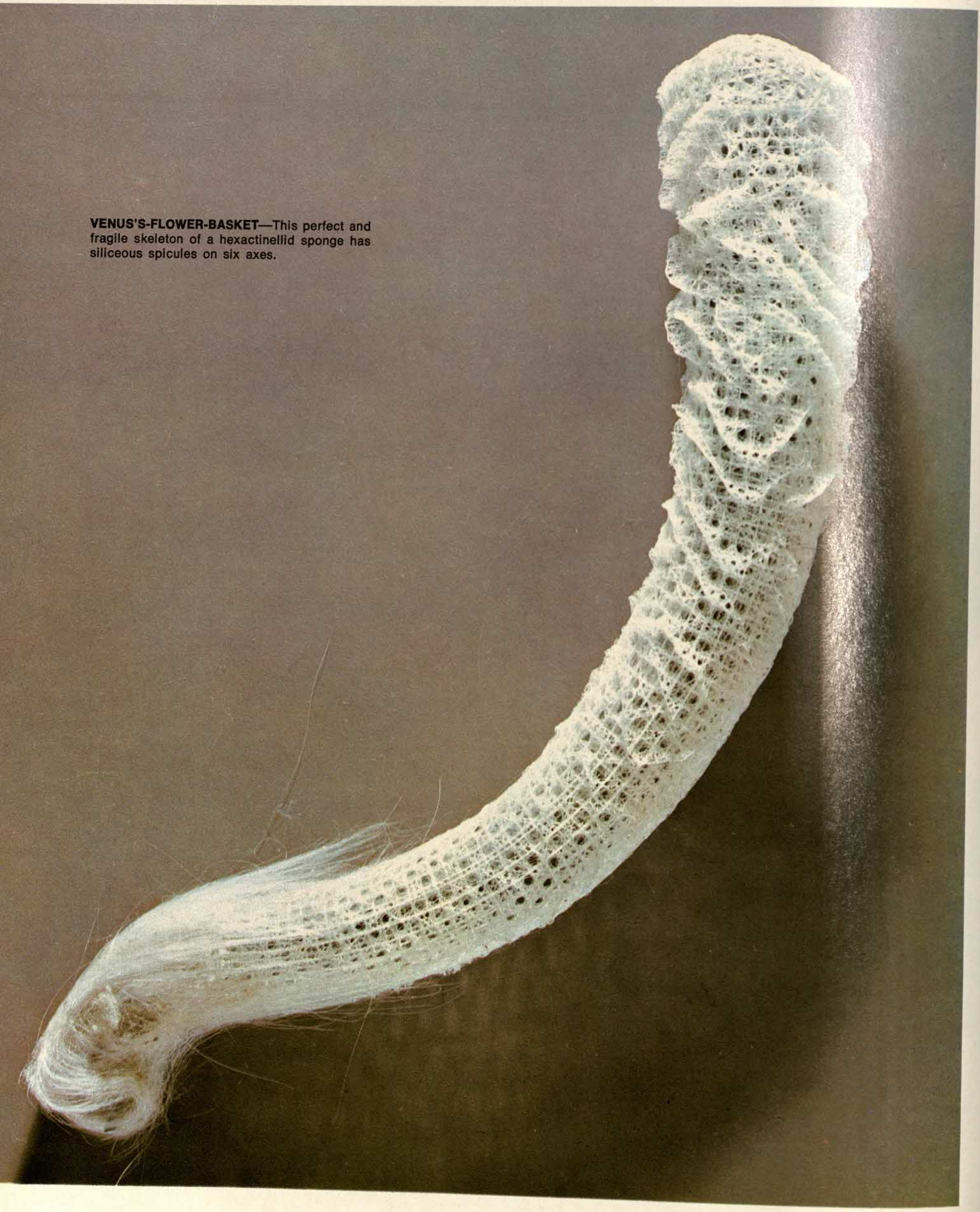
For example, the white blood cells of a human being are phagocytes that serve to engulf and destroy bacteria, dust, and other foreign matter that may enter the body.

structures and systems evolved.

The step-by-step enumeration of the development of unicellular organisms to multicellular organisms is hypothetical. No one knows for sure which step was first, which was second, and so forth. The first certain information available concerns the structure of the Porifera (sponges), the most primitive of all the multicellular organisms.

Fossil sponges are known from Cambrian and succeeding strata. The structure of the sponge's choanocytes is almost identical to that of the component cells of choanoflagellate colonies, and it is these zooflagellates that are usually thought to be the most probable ancestors of the sponge.

THE SPONGE | an animal that has defied evolution



VENUS'S-FLOWER-BASKET—This perfect and fragile skeleton of a hexactinellid sponge has siliceous spicules on six axes.

A careful study of the sponge reveals that this rather large many-celled animal has an extremely primitive structure. The fossils of sponges that lived about a billion years ago indicate that almost no change occurred during that time, except perhaps for an increase in size. By the Cambrian period (some 560 million years ago) the sponge had already reached the size of existing types. This has led to some speculation that the history of the sponge contradicts the theory of evolution. However, although many other species of organisms have been unable to evolve and, failing to overcome the processes of natural selection, have become extinct, the sponge, with its curious shape, has always been able to live in the seas. The reason for this successful resistance to the evolutionary process cannot be given with the present limited knowledge of genetic phenomena that underlie that process. Evolution is based on mutation; lack of evolution must result from lack of mutation. Perhaps the hereditary genes of the sponge resist the stimulants to mutation.

A sponge is a filter-feeding animal that circulates water through a system of channels in its body and feeds on the very tiny organisms and particles in the water. The outer dermal membrane of the sponge is perforated with pores that allow the water to enter. The motile power for the water currents within the sponge is provided by the coordinated whipping action of flagella on collar cells that are grouped in the interior of the sponge. Between the dermal membrane and the collar cells are cells of various sorts, some of which secrete supporting fibers of protein or spicules of calcium carbonate or silicon dioxide.

SKELETONS OF SPONGES

The skeleton is an important part of a sponge, because it gives the organism the rigidity necessary to keep it from collapsing, to keep the pores open, and thus to allow the water—which provides food and oxygen—to circulate freely. Sponge skeletons have many shapes, but all have a reticulated or lattice structure with a wide mesh; this structure serves to support the soft, "spongy" part of the organism.

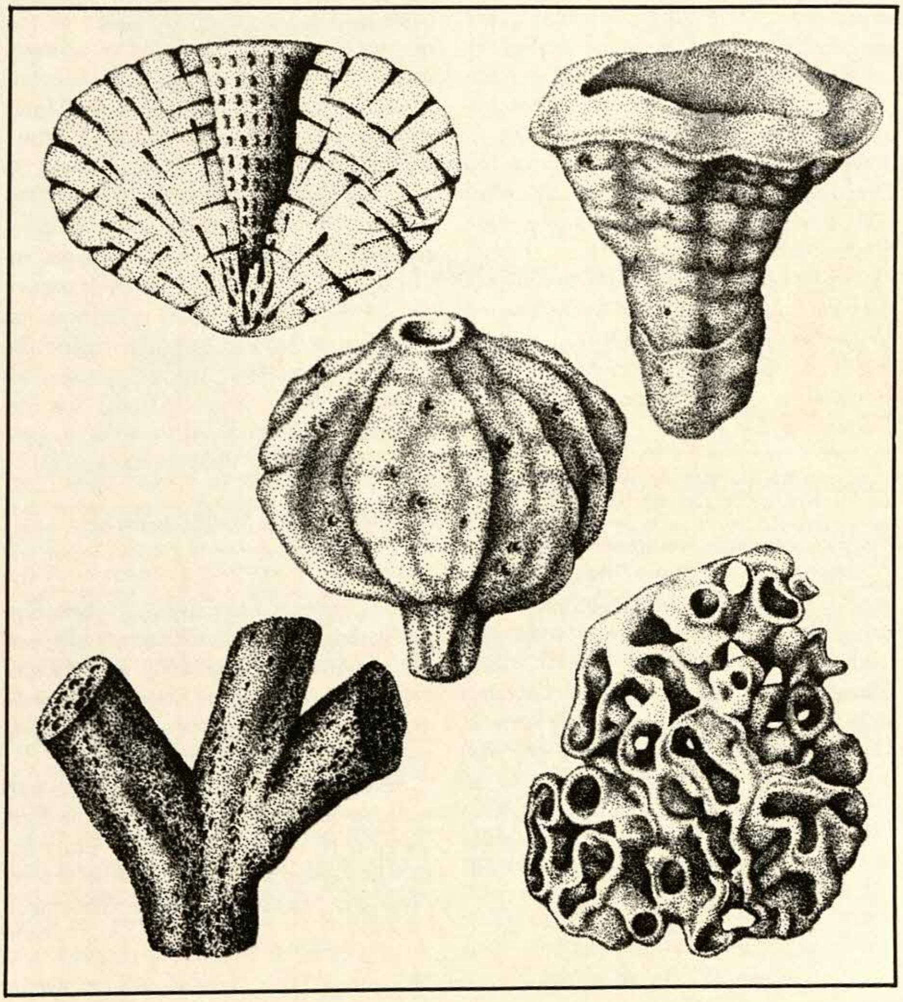
The elementary building blocks of the skeletons are arranged in many ways, but they invariably form a kind of three-dimensional lattice, of which the basic unit is the spicule. Spicules vary considerably in size and shape: some resemble simple, one-pointed rods, others have two or more points, and still others have no points. The spicules of some sponges are arranged like the axes or coordinates used in geometry, while those of other sponges resemble rays directed from the center of a tetrahedron toward its vertices.

The shapes of the spicules and the types of lattices they form are used in identifying and classifying sponges. The lattice of a hexactinellid (an example is shown in Illustration 1) has a square or cubical mesh. Although the pattern is not maintained throughout, the construction is perfect. Other kinds of sponges exhibit different types of square and cubical lattices, as well as lattices with a triangular mesh and those with an irregular mesh. The variety is astounding.

CLASSIFICATION OF SPONGES

Sponges belong to the phylum Porifera, which is subdivided into three classes on the basis of chemical composition of the spicules or skeletal elements.

SPONGES OF MANY SHAPES—Sponges have achieved great variety in their shapes; but the basic arrangement is the same for all: a hollow container with an aperture. Seawater enters the container through pores in its walls, circulates, and leaves through the aperture, known as an osculum. The shapes illustrated here are respectively those of *Astylospongia, Chenendospora, Hallirhoa, Doryderma,* and *Plocoscyphia.* All these genera of fossil sponges had a stalk that attached them to the floor of the ocean, whether this be sand or mud, and allowed them to bend. Each sponge is different in structure, but all are composed of the same basic spicules.



The class Calcarea includes species with one- to four-rayed spicules consisting of calcium carbonate. Representatives of this class may be found with compact, vase-shaped structures, with a loose network of thin tubes, or as irregular massive colonies. They are chiefly small organisms inhabiting the shallow waters of all seas. A few species of Calcarea are found at depths of 800 m (about 2,625 ft).

Members of the class Hexactinellida (Hyalospongiae) have siliceous spicules that are basically six rayed, but they are lacking in spongin, the protein substance that gives commercial sponges their great flexibility. Hexactinellids are exclusively marine organisms, occupying the deeper waters of all seas from depths of about 25 m to 8,500 m (about 80 ft to 28,000 ft).

Finally, the class Demospongiae includes species with siliceous spicules that are usually one to four rayed, but never six rayed. Fibers of collagenlike protein (spongin) are often present as component supporting structures along with siliceous spicules. In some species of the Demospongiae, including the so-called bath sponges of commercial value, such fibers constitute the sole intrinsic skeletal elements. Representatives of this class are the most abundant and widely distributed of all the sponges. They live at various depths in the sea. The only family of freshwater sponges (the Spongillidae) belongs to this class.

FOSSIL SPONGES

Both calcareous sponges and siliceous sponges have left fossils that consist almost exclusively of inorganic matter; the organic material that once formed the bodies of the organisms has left slight traces at most, and these can be detected only by very complicated procedures. If the rock containing the fossil is split and subjected to the chemical reaction of acids, delicate variations in composition may be detected that reflect differences in the organic composition of the soft parts of the sponge.

Fossils that have been subject to prolonged submersion in water may cause special difficulty. For example, calcareous skeletons may have been transmuted into siliceous skeletons because one material is substituted, over a long period of time, for another (as in the petrifaction of wood). The paleontologist must track down the original composition of the material that composed the skeleton.

Sponges are relatively unimportant fossils. A fossil is usually considered important if it belongs to an organism that lived briefly and hence indicates a definite period or epoch, thus identifying the time of the strata in which it is found; such a fossil is called an index fossil. An index fossil may also be important to geologists by helping them reconstruct an environment; for example, it may give evidence of the depth of water or the climate in which it lived. Now, sponges usually thrive best in hot climates, but not all sponges live in hot climates. Moreover, sponges thrive at various depths—some near the surface, some at about 30 m (about 100 ft), others at 100 or 200 m (about 300 to 600 ft), and a few at abyssal depths. Therefore, fossil sponges indicate very little about the environmental depths of the original organisms. As a matter of fact, in order to define the marine environment of fossil sponges, all the other fauna associated with the fossils must be considered in order to provide evidence for definite statements.

ASSOCIATION WITH OTHER ORGANISMS

Living sponges have many relationships with other organisms. Chitons, snails, certain nudibranch mollusks, and various fish prey on sponges. Larvae of certain neuropteran insects (sponge flies) live in and feed on freshwater sponges.

Many kinds of animals occupy the natural cavities of marine sponges or form burrows of their own, but the exact nature of these relationships is little known. Hydroids, sea anemones, zoanthids, nematodes, polychaetes, octopuses, copepods, barnacles, isopods, amphipods, shrimps, brittle stars, and fish are among the animals that dwell in either temporary or permanent association with sponges.

Pairs of shrimps (*Spongicola*) often inhabit the spongocoel or internal cavity of Venus's-flower-basket (*Euplectella*). Presumably, the shrimps are imprisoned for life in the rigid siliceous reticular skeleton of this sponge.

Suberites domunculus (class Demospongiae) habitually lives on snail shells that are occupied by hermit crabs. Decorator crabs often plant or hold on their backs pieces of sponge; this behavior may serve to hide or camouflage the crabs.

Hydroids, bryozoans, ascidians, and other encrusting animals compete with sponges for substrate. They may overgrow sponge colonies or be overgrown by them.

Many freshwater and shallow-water marine sponges harbor unicellular green algae in their amoebocytes (cells that carry food to other cells). The sponges probably obtain some nutriment from the algae in the form of sugars, inasmuch as the algal cells fail to synthesize starch when growing in sponges. In addition, the sponges may consume dying algal cells. Apparently both the algae and the sponges are able to survive independently. Young sponges are reinfected with algae from free-swimming algal zoospores in the water.

Unicellular and filamentous blue-green and green algae, as well as coralline algae, often grow in sponge colonies.

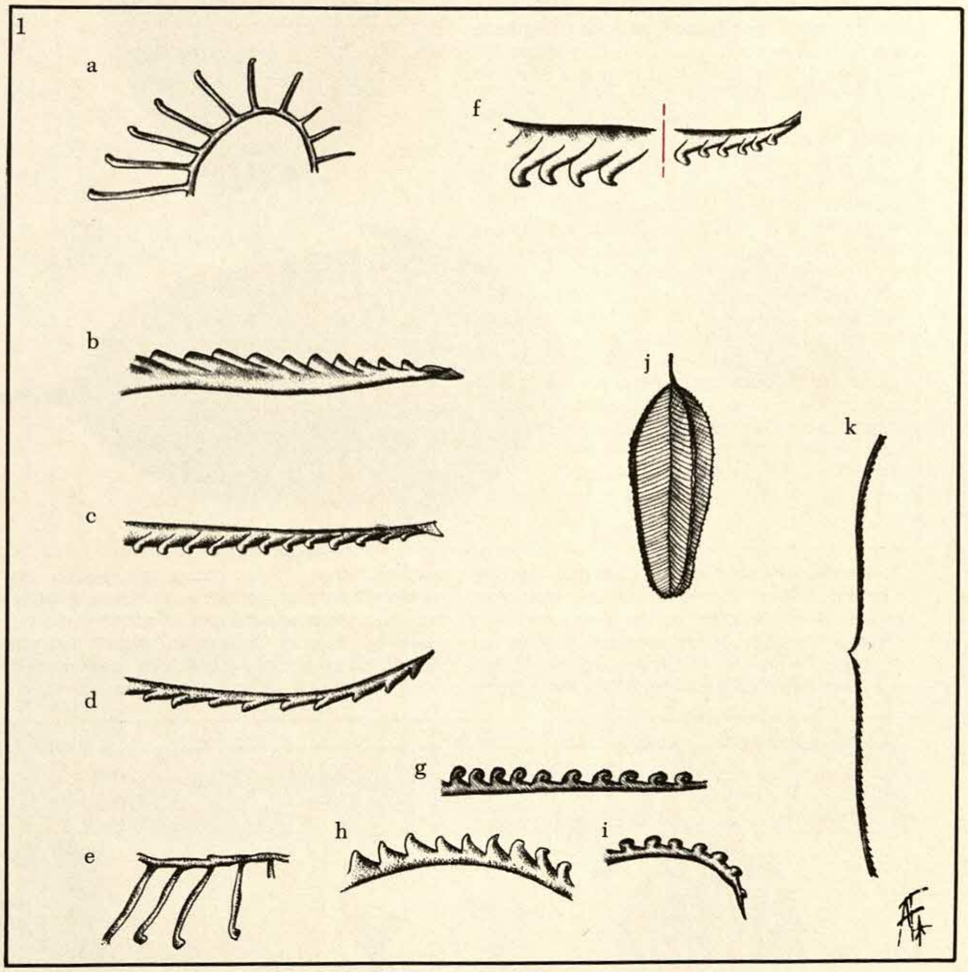
ECONOMIC IMPORTANCE

Synthetic plastic sponges have largely replaced natural sponges for household use. Nevertheless, natural sponges are still in demand for use by artisans and surgeons.

Certain kinds of sponges live in galleries excavated in corals, limestone, and other calcareous materials. They weaken limestone breakwaters and render oyster shells difficult to process.

FAUNA OF THE ORDOVICIAN AND SILURIAN PERIODS

graptolites, trilobites, and other characteristic animals



THE LARGE FAMILY OF GRAPTOLITES—The graptolites were so plentiful and widespread during the Ordovician and Silurian periods that these portions of geologic time are considered to constitute the "Age of Graptolites." These colonial animals exhibited great diversity in the numbers and positions of their branches. Graptolites of the early part of the Ordovician possessed many branches; as these organisms evolved, they tended to have fewer and fewer branches. Graptolites of the Silurian, for the most part, were distinguished by single branches. Some common monograptids (single-branch graptolites) are shown in Illustrations 1a through 1i. Illustrations 1j and 1k show representative dichograptids (branched graptolites). The specimen in Illustration 1j has a leaflike shape.

The last part of the Silurian period was characterized by an important event: the invasion of the submersed lands by living organisms. Up until this time, lifeforms had been confined to existence in a watery environment. They had multiplied and diversified and diffused throughout the seas of the Earth. Through the evolution of a variety of structures, they had become adapted to many different habitats. Some of them perhaps had even begun to breathe air.

Nevertheless, the invasion of the terrestrial environment was not the only important development of Ordovician and Silurian times. The Ordovician period was characterized by the existence of many lime-secreting organisms, including brachiopods, bryozoans, clams, corals, snails, and trilobites. Ordovician rocks are particularly rich in the calcareous shells and carapaces of these animals.

The trilobites, which were present in the Cambrian, experienced their maximum development during the Ordovician. Many species appeared and disappeared as specialization occurred. Certain species evolved a form of defense in which they curled into balls. Some varieties attained relatively large size; the largest specimen reached a length of about 76 cm (about 30 in.).

The cephalopods were the largest invertebrates of the Ordovician period; some had shells that were about 4.5 m (about 15 ft) long. Graptolites were more plentiful and more widely distributed during this period than during any other time in Earth history.

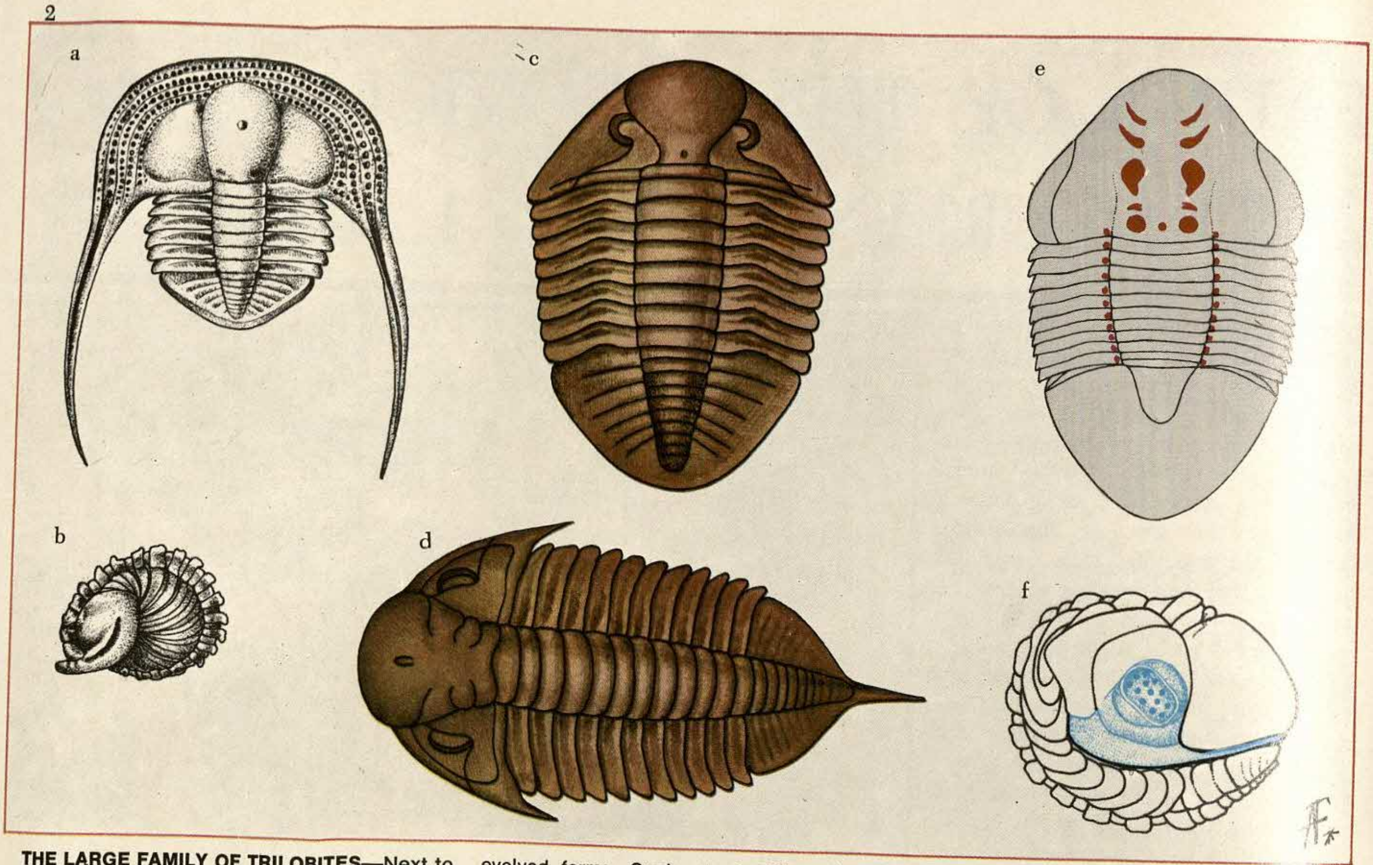
One other significant development of the Ordovician was the appearance of primitive fish, the earliest vertebrates.

During the Silurian, the brachiopods, bryozoans, cephalopods, and corals remained important, as did the trilobites, although the latter declined somewhat. Echinoderms and sponges were also present in Silurian waters. Of the echinoderms, the crinoids underwent the greatest differentiation of species. Graptolites that differed from those prominent during the Ordovician also existed in great numbers.

Just as some of the primitive cephalopods had attained enormous proportions, certain primitive arthropods, the eurypterids or sea scorpions, grew to gigantic size. Indeed, the largest arthropod ever known was a Silurian eurypterid that measured about 2.5 m (about 9 ft) in overall length.

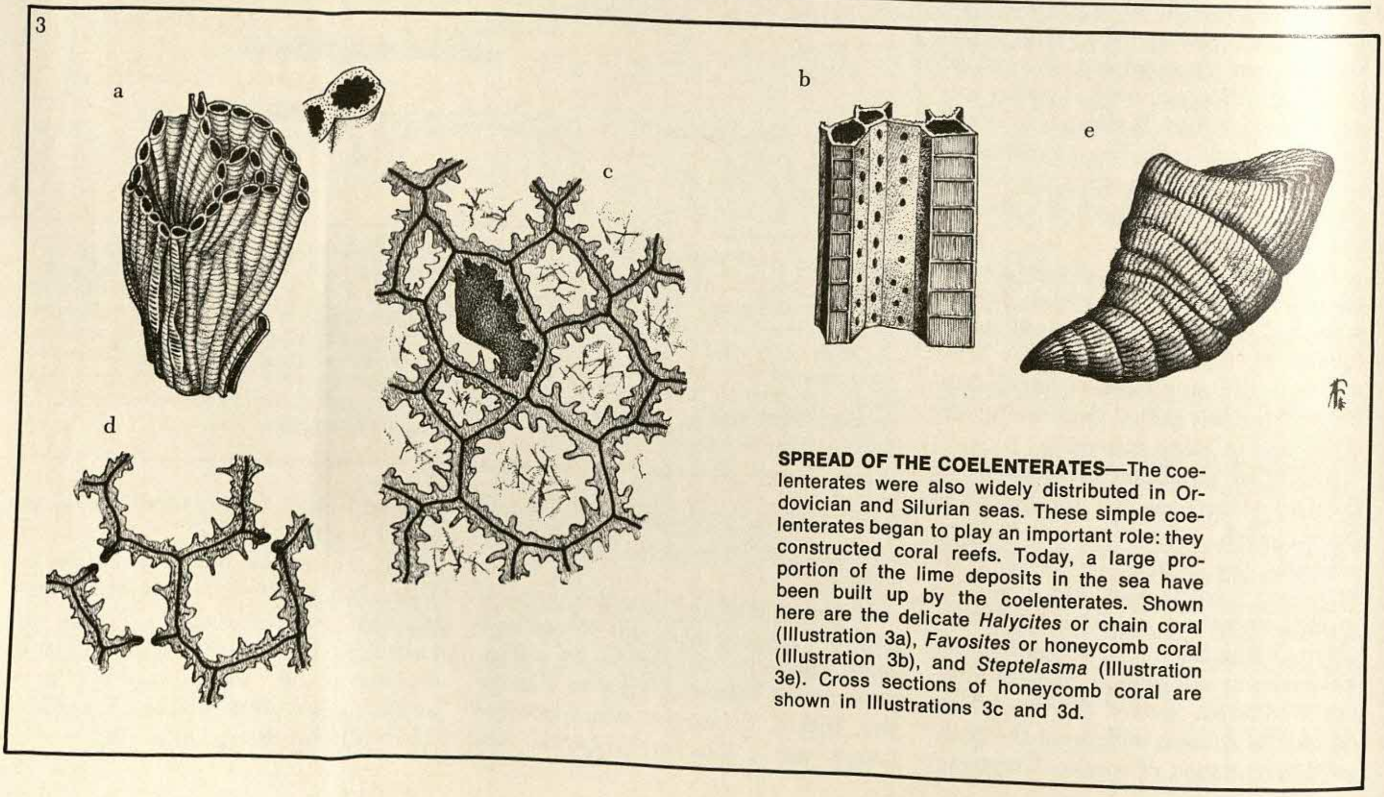
Fish, which had appeared during the Ordovician, evolved very slowly. These primitive vertebrates of the Silurian remained small, with a maximum length of about 15 cm (about 6 in.), and their jaws remained poorly defined. The oldest known fish fossils are Ordovician.

2

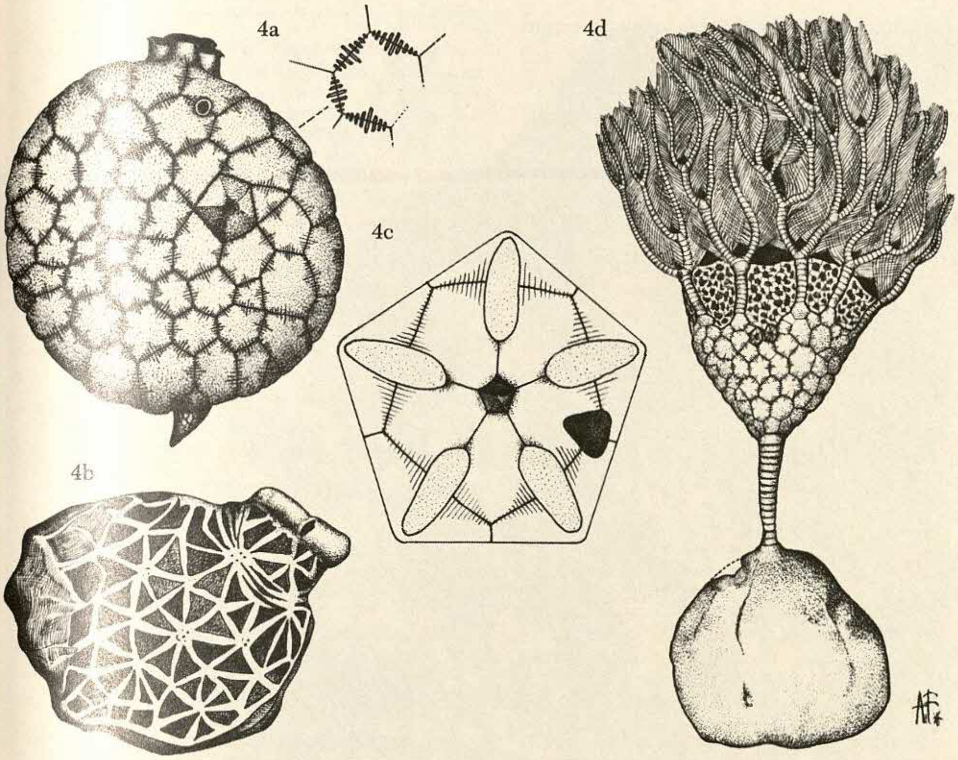


THE LARGE FAMILY OF TRILOBITES—Next to the graptolites, the trilobites are the most characteristic animals of the Ordovician and Silurian periods. These animals survived as a group throughout the entire Paleozoic era. The illustrations show some of the most highly evolved forms. *Onnia ornata* (Illustration 2a) of the Ordovician period was a large trilobite with two great appendages. *Flexicalymene* (Illustration 2b), an Ordovician animal, had the ability to curl up into a ball; this adaptation, a form of passive defense, was also characteristic of *Phacops* (Illustration 2f), a trilobite of the Silurian and Devonian periods. Other typical trilobites depicted here include *Asaphus* (Illustration 2c) of the Ordovician period, and *Dalmanites* and *Illadnus* (Illustrations 2d and 2e) of the Silurian period.

3



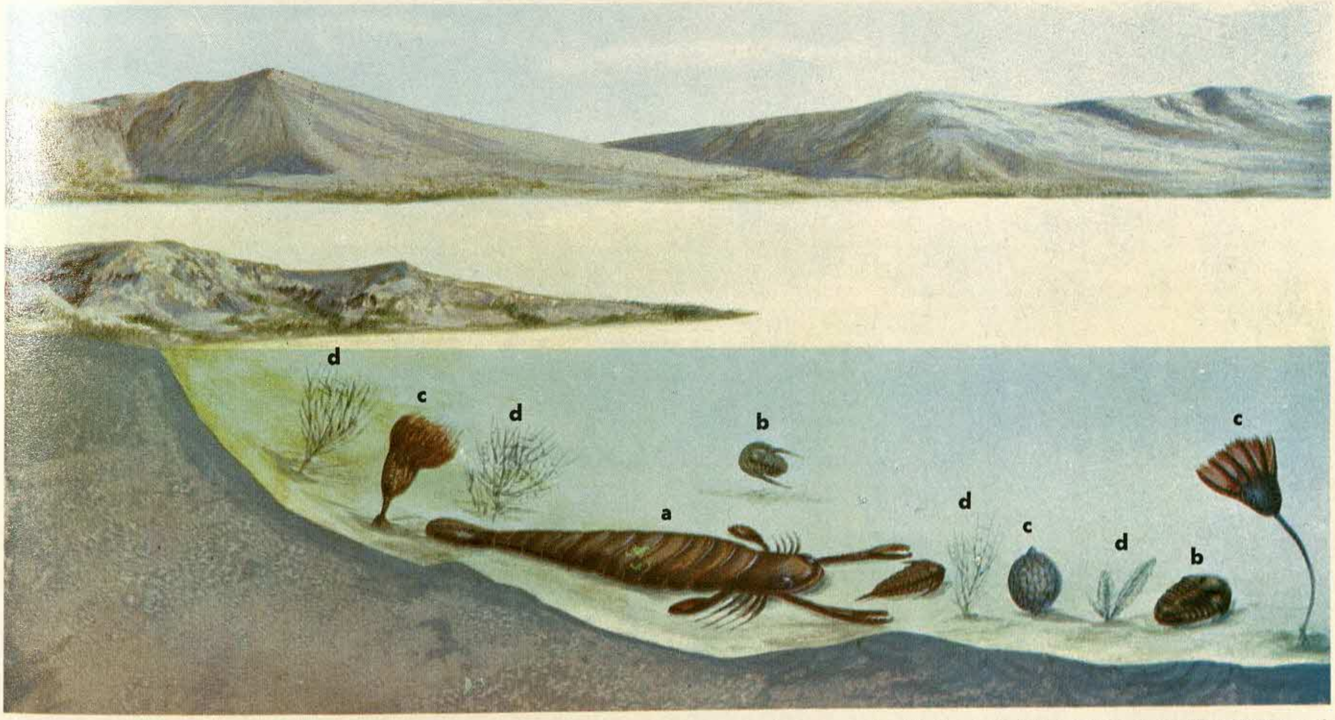
SPREAD OF THE COELENTERATES—The coelenterates were also widely distributed in Ordovician and Silurian seas. These simple coelenterates began to play an important role: they constructed coral reefs. Today, a large proportion of the lime deposits in the sea have been built up by the coelenterates. Shown here are the delicate *Halycites* or chain coral (Illustration 3a), *Favosites* or honeycomb coral (Illustration 3b), and *Steptelasma* (Illustration 3e). Cross sections of honeycomb coral are shown in Illustrations 3c and 3d.



THE ECHINODERMS—A large number of Ordovician and Silurian animals belonged to the group of spiny-skinned organisms known as echinoderms. The illustrations show the structures of several echinoderms from the Ordovician and Silurian periods: *Echinosphaerides* (Illustration 4a); *Heliocrinus rouvillei* (Illustration 4b); *Codaster trilobatus,* with its oral cavity visible (Illustration 4c); and *Schiphoerinus elegans* (Illustration 4d).

Thus far, no mention has been made of the unicellular organisms and plants that were important during this phase of Earth history. Most of the animals of the time fed on plankton, single-celled organisms that drifted in the seawater. During the Ordovician and Silurian, eating was a relatively simple matter, almost as simple as it had been for the unicellular organisms of the Cambrian. Seawater flowed through the walls of the organism and planktonic food particles were trapped by cilia. This was a quiet process; hunting did not exist, because the animals had limited locomotion and most of them lacked sense organs. Finally, these organisms lacked digestive systems capable of assimilating large chitinous animals.

5



THE LANDSCAPE DURING THE ORDOVICIAN AND SILURIAN PERIODS—Throughout the Ordovician and most of the Silurian, the land was barren of life. Probably only during the last part of the Silurian did the first forms of life venture onto the land. Therefore, only then did small patches of greenery appear on the landscape. The shallow sea near the land was occupied by different kinds of animals, some of which occasionally and briefly ventured onto the shore. The organisms populating the sea floor exhibited great variety of sizes and shapes. The eurypterid, *Pterygotus buffaloensis* **a** was the largest arthropod ever to have lived; despite its primitive organs of locomotion, this animal moved very quickly. Various kinds of trilobites **b** rested on the bottom and glided through the water. Echinoderms **c** and graptolites **d** were plentiful.

In addition to the animals shown in the illustration, many kinds of mollusks, including gastropods, populated the sea floor. Coral reefs existed at all latitudes, with gastropods and algae attached to them.

THE ECHINODERMS | spiny-skinned marine animals

← **A MOBILE ECHINODERM**—The starfish, a member of the class Asteroidea, has a characteristic five-rayed symmetry. (In fact, such a symmetry is a characteristic feature of most classes of echinoderms.) The starfish has a rather flat, stellar body, with five or more arms. Fossil remains of starfish have been found in rocks that date back to the Lower Silurian. However, such fossils are rarely well preserved; the calcareous plates constituting the skeleton are often incompletely fused with one another and, consequently, are easily separated and lost in the sedimentary deposits.

The forms of some living organisms are so fantastic that a layman might assume that they came from some distant planet. The forms of many primitive organisms might evoke a similar assumption. Among the animals whose forms are strange, but often exquisitely beautiful, are the members of the phylum Echinodermata.

The echinoderms are ancient animals, dating back at least to the early part of the Paleozoic era. Present-day representatives of this phylum differ somewhat from their predecessors and bear witness to the evolution of living forms in well-delineated directions. Animal forms undoubtedly had their origins in single-celled organisms, such as the Protozoa. Among the earliest phyla to emerge were the Porifera (sponges) and the Coelenterata (coelenterates). From these very primitive groups, others branched out in two main directions—one evolving in the direction of the Arthropoda (insects, spiders, and other animals with jointed legs), and the other evolving in the direction of the Chordata (animals with backbones). The echinoderms constitute an important intermediate group in the progressive evolution from the coelenterates toward the higher forms of life.

PRIMITIVE STRUCTURES

The most primitive forms of life were unicellular organisms, which obtained nourishment from the water in which they lived by a process of diffusion. In a second stage, multicellular organisms appeared, and specialization of body parts began to take place. As evolution proceeded, animals acquired not only specialized organs, but also specialized systems.

In the hierarchy of living organisms, based on the complexity of structures, the sponge is superior to a protozoan, because it consists of specialized tissues that provide for support, nourishment, and other requirements. Furthermore, the structure of the sponge permits this organism to take advantage of the motion of the water, from which it derives its nourishment, filtering it in a very efficient manner. However, the sponge is immobile; it is an organism fixed in one place. A living organism that is capable of motion is superior to the sponge, because it can take greater advantage of the distribution of food in the water.

Different types of motion may be distinguished. Organisms with passive motion are carried along by the currents and other movements of the water. Passive motion offers advantages over life in a fixed location, because it provides the organism with the possibility of being carried to new places, where perhaps new sources of food are available; on the other hand, passive motion offers a disadvantage in that the organism may

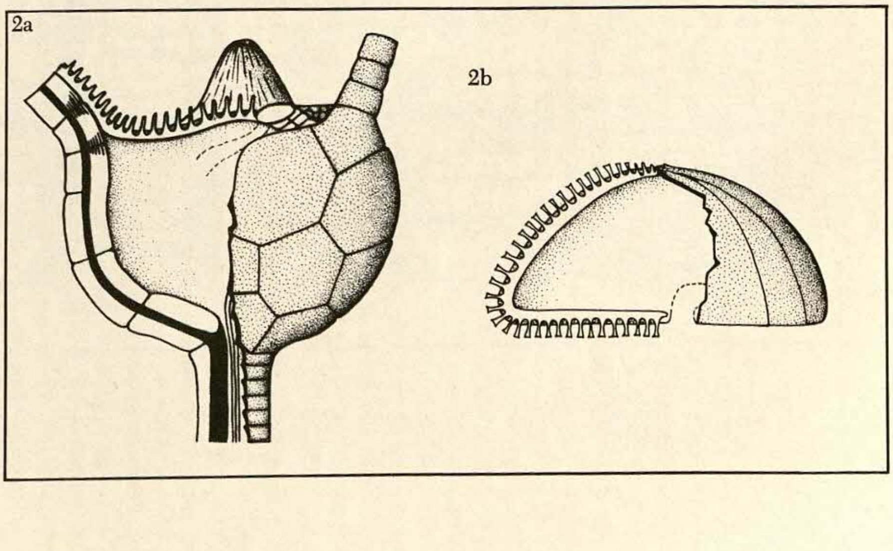
SESSILE AND MOBILE ECHINODERMS — A single, simple description of echinoderm structure is inadequate, because the various echinoderm species are differentiated into such a variety of forms that no one organ or structure characterizes the entire phylum. Nevertheless, the forms of the sessile and mobile echinoderms may be contrasted in a rough or general fashion. These two (schematic) diagrams serve to emphasize the differences between the types.

The fixed or sessile echinoderm (Illustration 2a) has a structure known as a peduncle or stem, by which it is attached to the sandy or rocky bed of the sea. The body consists of a vessel, called the theca, which varies in form, sometimes being spherical or subspherical. The theca is protected by plates of calcium carbonate or magnesium carbonate. Toward the top of the body is the mouth, the orifice through which food is taken into the body. In the fixed echinoderm, the mouth serves no other function; it is incapable of seizing food or chewing it. The functions of capturing food and conveying it to the mouth are performed by tentacle-like appendages. These tentacles also serve a respiratory function, fixing the oxygen dissolved in the seawater. In the fixed type of echinoderm, the anus (the orifice through which waste products of digestion are eliminated) is located next to the mouth, on the upper surface of the body. Interestingly, although the plates that constitute the body skeleton (theca) are usually fused together to form a completely rigid structure, the plates of the peduncle and other protuberances are articulated, giving these structures flexibility. The plates are surrounded by a musculature traversed by a primitive nervous system.

The structure of the mobile echinoderm (Illustration 2b) is quite different from that of the fixed echinoderm. It reveals some important tendencies in the arrangement of organs that are also found in higher animals. First of all, the mouth and anus are located at opposite extremities of the body. In echinoderms that can move rapidly in any direction—that is, in those organisms showing no preference for a particular direction of movement—the mouth is located on the lower part of the body, and the anus is located on the upper part of the body. In echinoderms with a preferred direction of movement, the mouth is situated in the anterior portion of the body, and the anus is located in the posterior portion of the body. Sometimes the mouth is equipped with bony plates that are especially adapted for chewing and breaking the hard parts of small brachiopods and other organisms constituting the echinoderm's diet.

The ambulacral tentacles (tube feet) of the mobile echinoderm are much more sensitive than the tentacles possessed by a sessile echinoderm, and these structures serve ambulatory or locomotive functions.

This discussion briefly stresses the substantial differences existing between the sessile and mobile echinoderms. The differences lie principally in the arrangement and specialization of the organs and in the increased sensory and motor functions of the mobile echinoderms.



be carried to places where no food is available or where that organism may become food for some other organism. Evidently much greater possibilities are provided by active, voluntary motion that can be directed toward the places indicated by the sense organs.

An analogy may be drawn between the organization and operation of a factory and the organization and function of a living organism. In a factory, raw materials are brought into the installation, where they are processed, and the finished products are taken out. The various departments of the factory may be arranged in a number of ways, but they must be well connected and consecutive, and their operations must be well coordinated. If the production process is to be mobile—that is, if the operations are to be carried out on a ship, airplane, or truck—the organizational possibilities are limited, for the problems of fitting the various components into a small space and making their operation as efficient as possible are not easily solved.

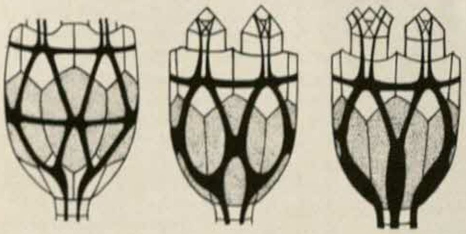
Similarly, a living organism must exchange materials with the outside world (environment). The various organs and systems of a living organism may be arranged in a great variety of ways also, and these components must be interconnected and coordinated to enable the organism to cope successfully with its environment.

Echinoderms lend themselves to this factory analogy, because they exist in both fixed and mobile forms. A study of the echinoderms reveals the evolution of the structures and arrangements of the organs according to the limitations imposed by fixity and mobility.

FOSSIL ECHINODERMS

A great amount of information has been accumulated about extinct classes of echinoderms from the Paleozoic strata. As only the skeletons are preserved, however, much of what has been written about the soft parts is hypothetical—based as it is on knowledge of modern forms and their development. Among the present-day echinoderms, the surviving crinoids represent the most archaic type. Crinoidea include the attached, stalked sea lilies as well as the stalkless, free-living feather stars. The sea lilies, which flourished in former geological periods, are important index fossils. Crinoids had their greatest recorded expansion of numbers and kinds in the Silurian period, which began approximately 435 million years ago.

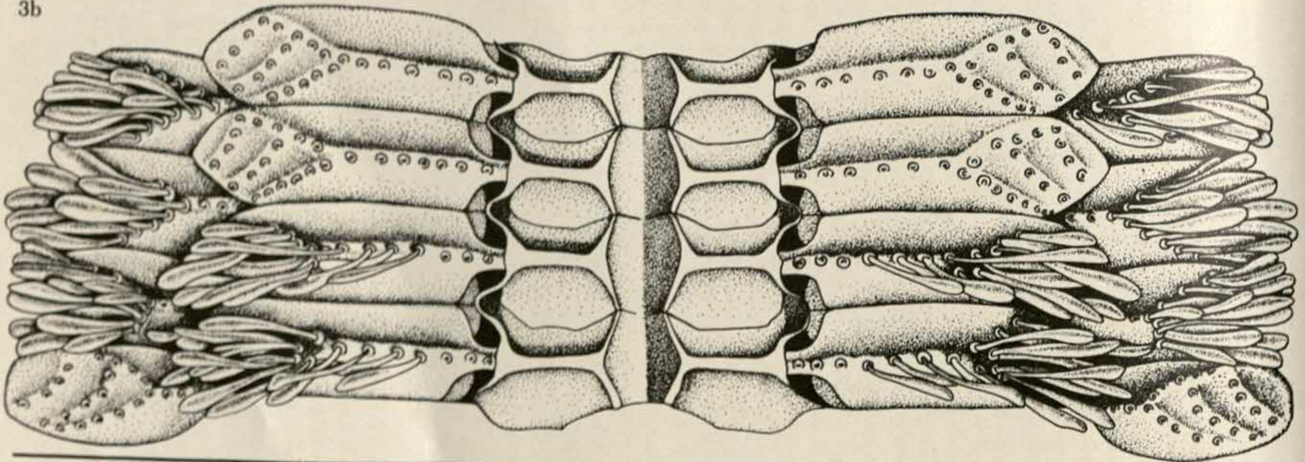
3a



THE MARVELOUS FORMS OF THE ECHINODERMS—Notwithstanding the relative simplicity of echinoderm structures, many of these organs have marvelous forms. Illustration 3a presents some of the arrangements of the nerve cord surrounding the thecae of crinoids. Each of these arrangements permits a distribution of the nerve branches over the entire surface of the animal's body.

Illustration 3b shows the structure of a fragment of an arm of a common starfish of the Silurian period, *Platanaster ordovicus*.

3b



ANCIENT ANCESTORS OF MAN

the primitive echinoderms

Many zoologists speculate that the most primitive chordate forms were derived from the echinoderms (phylum Echinodermata). The animals, which have occasionally been described as organisms in search of a shape, may, therefore, be considered as the most ancient ancestors of the mammals—and of man. The various kinds of echinoderms have organs with remarkably different structures; this fact demonstrates the adaptability of these animals to different modes of life. Some of them live stationary existences, fixed to the floor of the sea, while others are more or less free to move about.

The trilobites possessed a primitive means of locomotion, but the echinoderms that are mobile utilize an even more primitive method of movement. These organisms are furnished with special structures known as ambulacral pedicels

1

RELATIVELY SIMPLE SHAPES—For about 150 million years, from the Cambrian period to the Devonian, members of the class Cystoidea of the phylum Echinodermata populated the seas of the world, often in great numbers. These primitive echinoderms attained their maximum distribution during the Silurian period.

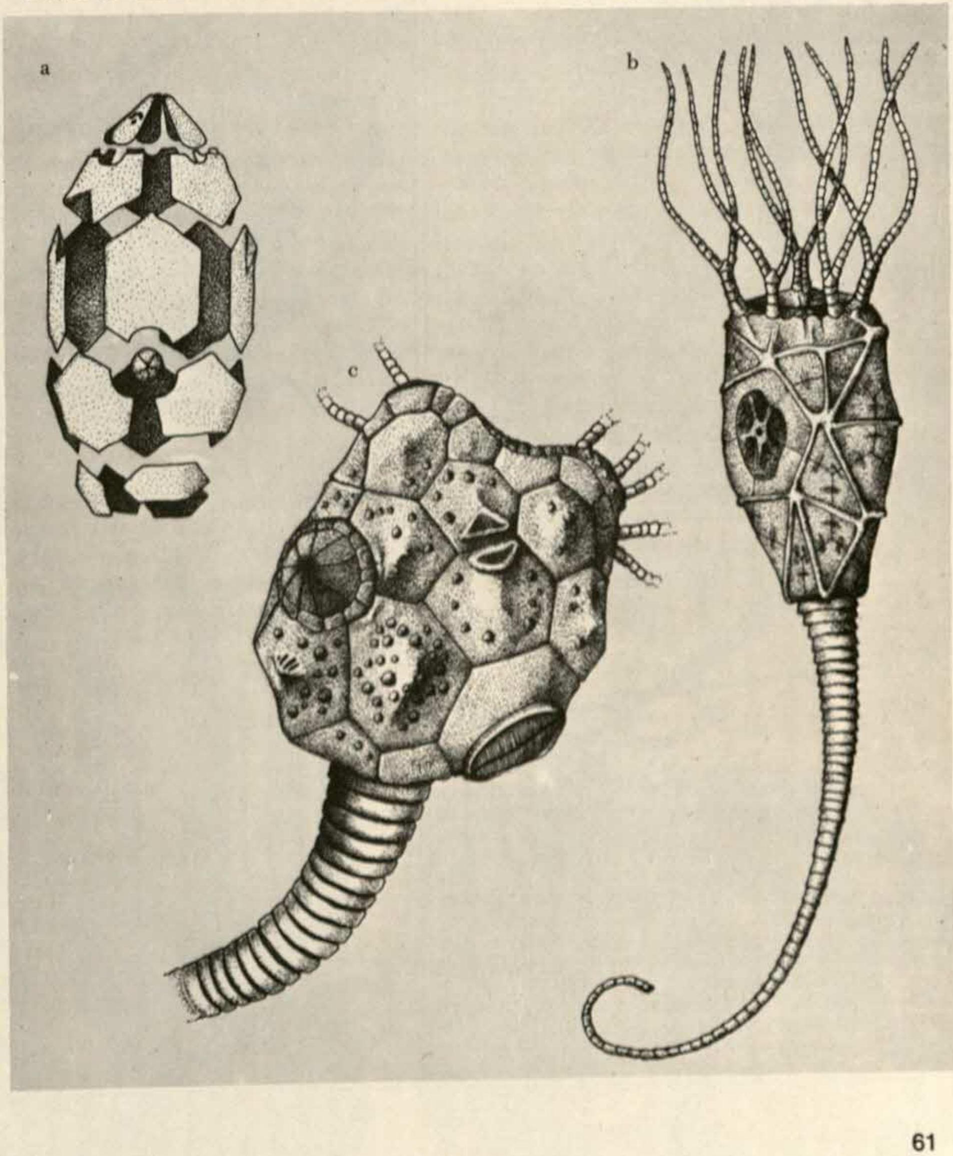
The body of the stationary cystoid was characterized by three main parts: the test or calyx; the peduncle, an often long, flexible stem with which it anchored itself to the sea floor; and tentaclelike appendages that provided for the collection and transport of food to the mouth. The test varied greatly in size, ranging from about 20 mm (about 0.8 in.) in some species and to about 40 mm (about 1.6 in.) in other species. The structure of the skeletal part of the test was an interesting characteristic of the cystoids; it was a type of shell formed by many interlocking calcareous plates. Each plate had its own form, and the contours depended on the position of the plate on the test.

The exploded view of the calyx of a rhombiferous cystoid (Illustration 1a) shows the approximate location of the plates. This plated structure was common to all the cystoids.

Macrocystella mariae (Illustration 1b) of the Cambrian period exemplified the overall cystoid structure. The organism reconstructed here possessed a stem a few centimeters long, a calyx about 20 mm (about 0.8 in.) long, and adductive tentacles or food brachioles that were slightly shorter than the calyx. Ornamentation of the calyx was a characteristic of this cystoid and of almost all the echinoderms. Each animal possessed unique deformations on the surfaces of the plates of the calyx; the ornamentation was omitted from Illustration 1a, because this drawing was intended to demonstrate the common underlying characteristics of a calyx. The thickness of the calyx varied from 1 mm (about 0.04 in.) to 1 cm (about 0.4 in.). Originally the calyx consisted of calcareous materials, but these were replaced by other materials during fossilization.

Schizocystis armata (Illustration 1c), a cystoid of the Silurian period, had food-gathering appendages of unknown length and a calyx formed by pentagonal or hexagonal plates covered with scant ornamentation. The oral aperture or mouth was located on the top part of the calyx, while the anal orifice was situated on the side at the point of the maximum circumference of the calyx.

Despite the fact that the remains of certain species have occasionally been found in abundant accumulations, echinoderm fossils are rare. Usually only the calyx is preserved.

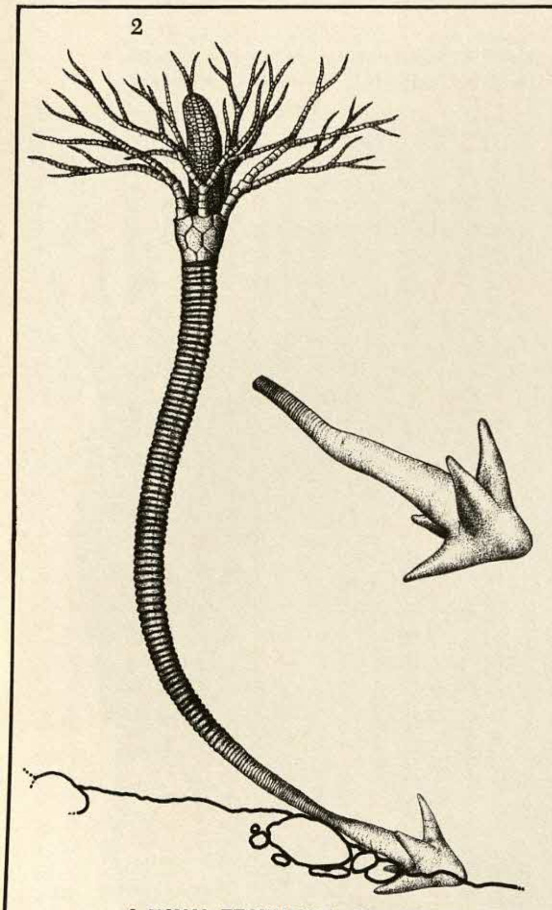


or tube feet that allow them to move about very slowly. These appendages protrude from the body through special pores; suckers on the ends of the pedicels serve as adhesive organs. The echinoderms are provided, then, not with agile paws, but with blunt protuberances, which by virtue of their numbers compensate in part for the inefficiency of each individual pedicel. The entire bottom areas of some echinoderms are covered with tube feet.

Echinoderms exhibit a great variety of shapes. Some are spheroidal, while others are polyhedral. Some look very much like plants, others are star-shaped, and still others combine several of these different characteristics.

This discussion is concerned with some of the more interesting and characteristic shapes of the more important classes of echinoderms. As usual, priority is given to those forms that have a certain importance as fossils. The importance of an echinoderm is not always judged in geological terms; in fact, for the paleontologist, the importance of a particular organism depends partly on how quickly the form of that organism changed and partly on the frequency with which the fossil of the organism is discovered. Echinoderms did not evolve with any particular speed; moreover, many stratigraphic gaps prohibit paleontologists from reconstructing their complete evolutionary history.

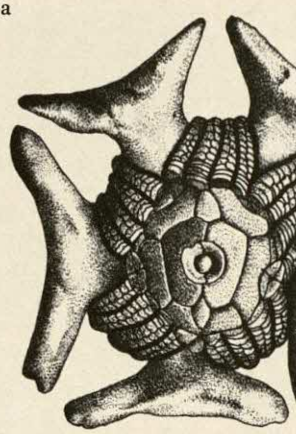
2



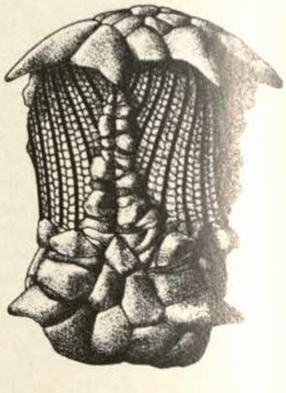
A NAVAL TECHNIQUE—The attachment of an organism to the sea floor always presents problems. Scientists have noted with interest a kind of convergence by which certain echinoderms formed roots scarcely distinguishable (in outer form) from the roots of plants. This illustration, however, shows the application of a naval technique of attachment. In fact, *Ancyrocrinus bulbosus* of the Devonian period in North America differed from all its sister species by possessing the ability to attach itself, by means of an anchor, to all but smooth, solid surfaces.

PROTECTION OF A WEAK POINT—The mouth constitutes a weak point in the echinoderm structure, because this opening leads to the inside of the test, where delicate organs are located. Echinoderms required some means of protecting the mouth against intrusions of extraneous bodies and incursions of predators. These illustrations demonstrate how different types of crinoids solved the problem of protecting the mouth. *Sterotocrinus bifurcatus* (Illustration 3a) developed a scaly roof in the shape of a mushroom top; this structure covered the mouth and the stomach sac. *Eucalyptocrinites rosaceus* (Illustration 3b), *Tholocrinus spinosus* (Illustration 3c), and *Pterotocrinus coronarius* (Illustration 3d) provide other examples of structures evolved for the protection of the mouth.

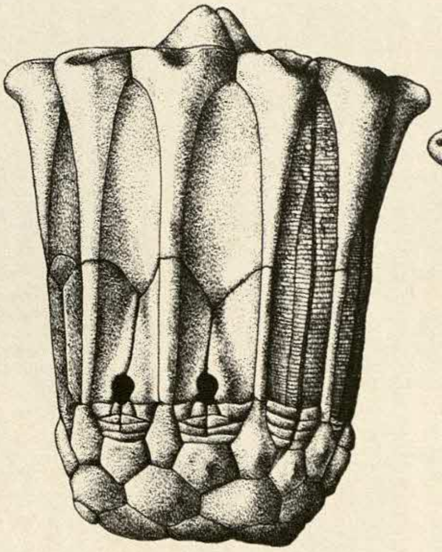
3a



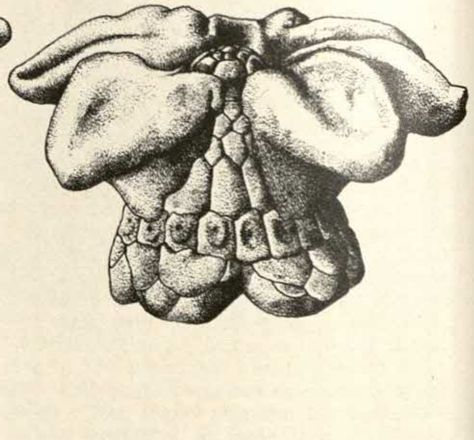
3b



3c



3d



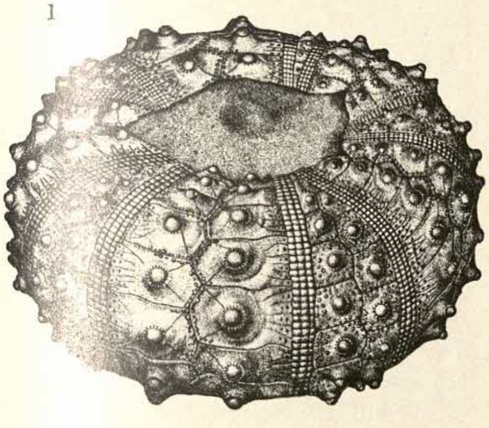
THE LONG HISTORY OF THE SEA URCHINS

an infinity of forms

In common with the other classes of echinoderms, the class Echinoidea, which includes the sea urchins, has had a long existence on the Earth. In fact, members of this class lived almost 500 million years ago, early in the Ordovician period of the Paleozoic era.

The sea urchins have compact bodies nearly spherical in shape. The skeleton, which lies under the epidermis and consists of calcareous plates that fit together tightly, is ornamented by rows of tubercles for the spines and openings for the tube feet. In life, the skeletons are not visible; when they are removed and cleaned, however, their distinctive patterns become convenient tools for identification and classification.

1



A VERY DELICATE STRUCTURE—Illustration 1 shows the skeleton of the extinct sea urchin *Phymosoma granulosum,* which was shaped like a sphere somewhat flattened at the poles. The ten narrow bands, or ambulacral plates, bore the tube feet. Spines occurred on the wider interambulacral plates.

The nearly spherical shape of the skeleton increases its strength and provides protection against the pounding of waves in the intertidal zones where some sea urchins live. Others prefer the calmer waters at greater depths. The sand dollars, which are much-flattened echinoids, live far from shore, and usually only their skeletons are found on beaches where they are cast up by waves.

An obvious feature of sea urchins is their bristly armor of spines that nature has provided to discourage hungry enemies. The size and shape of these spines vary greatly; some are about the size and shape of pencils, others resemble needles, and some are even club-shaped. Because each spine is mounted on a tubercle, the spines occur in rows. The chemical composition of the spines is largely calcium carbonate with some organic material (in some species the spines contain poison glands).

Another defense mechanism of the sea urchin is its array of *pedicellariae*—tiny pincers set on stalks and intermingled with the spines. Some of the pedicellariae are poisonous and cause pain, paralysis, or even death once their toxin is injected into a victim. Pedicellariae also catch food and clean the animals' surface.

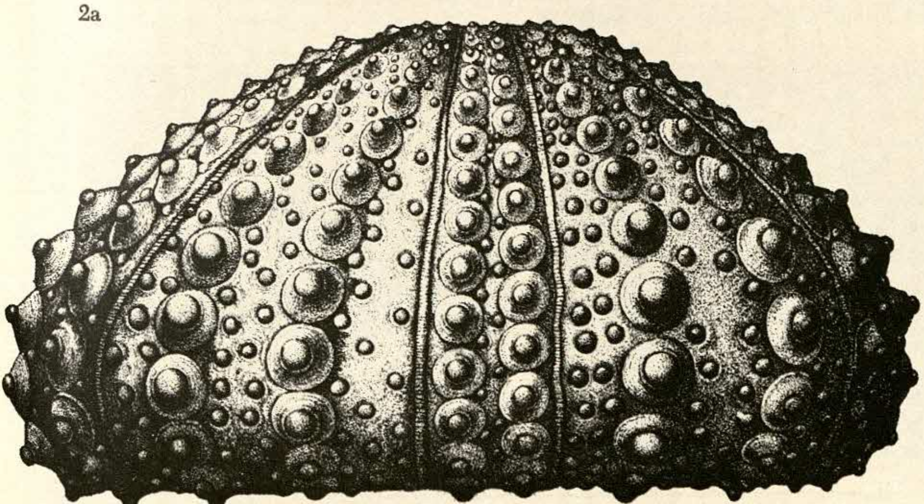
AN INFINITY OF FORMS

During their extremely long existence, the sea urchins have undergone great modifications that can be traced by observing fossils from different geological eras. Early sea urchins were hemispherical and perfectly symmetrical, their bodies covered by long spines like those of the present-day urchins. They rested on the sea bottom where they lived a stationary existence filtering food from the water.

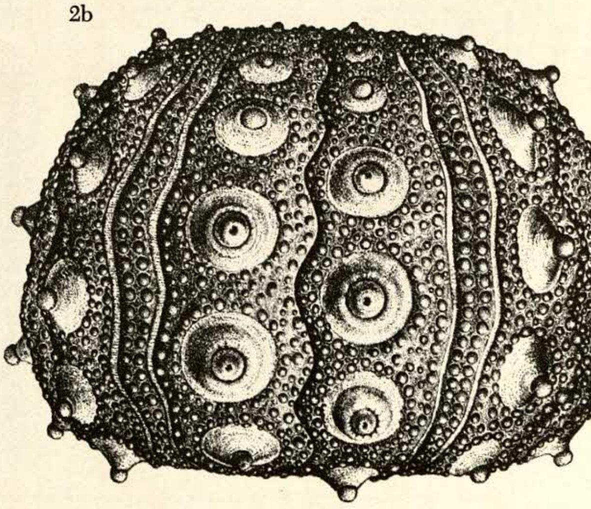
Later echinoids developed greater mobility and began their long evolutionary history. The shape of early sea urchins was symmetrical with respect to the vertical axis passing through the center of the body, with the oral pole at the bottom and the anal pole on the top. Some urchins retain this symmetry today; others became progressively more elongated, the direction of elongation coinciding with the direction in which the animal moved. The anus, initially placed in an upper position, moved to a location at the rear and, in the more highly evolved types, was brought all the way to the lower surface. Spines were modified substantially and some of them became shorter and thinner, resembling coarse hairs more than spines. In some echinoids the tube feet migrated to the lower surface where they were situated symmetrically around the oral opening; afterward they were concentrated near the rear of the animal. Some urchins developed unusual shapes resembling cones or hearts.

LIKE PRECIOUS JEWELS—These two fossil skeletons of sea urchins display a marvelous perfection of form. Illustration 2a shows a skeleton of *Pseudodiadema pseudodiadema,* which as its name indicates, was similar to a jewel in its patterns. Its flat lower surface rested on the sea bottom. *Paracidaris florigemma* (Illustration 2b) has a similar form, but seems less flattened than that of *Pseudodiadema pseudodiadema.* Both of these specimens, like other sea urchins, have pentagonal symmetry.

2a



2b



ANIMAL LIFE CONQUERS DRY LAND

a landmark in evolution

By the end of the Silurian period living things had come to occupy the seas, from the great depths to the shallow beaches. The forms of these organisms had evolved, gradually becoming more complex and efficient as they adapted to the varying conditions of the different habitats and niches of the marine environment. In the latter part of the Silurian period, living forms had evolved sufficiently to begin the transition from watery surroundings to dry land. The emergence of life from the aquatic environment onto land must be viewed as a great event in the evolutionary process, for on land, life forms were to undergo spectacular diversification in structures and behavior patterns—diversification far exceeding that which had already taken place in the seas.

Any biotic form perfectly adapted to one habitat has great difficulty surviving in a different environment. It is precisely this perfect adaptation of certain species that makes their rapid insertion into a new environment impossible. To complete the transition from water to land—a process that undoubtedly took millions of years—living organisms had to overcome many obstacles.

OBSTACLES TO SURVIVAL

Major obstacles to the survival of animals on land involved the acquisition of food and oxygen, the provision of support, and adaptations for locomotion and reproduction.

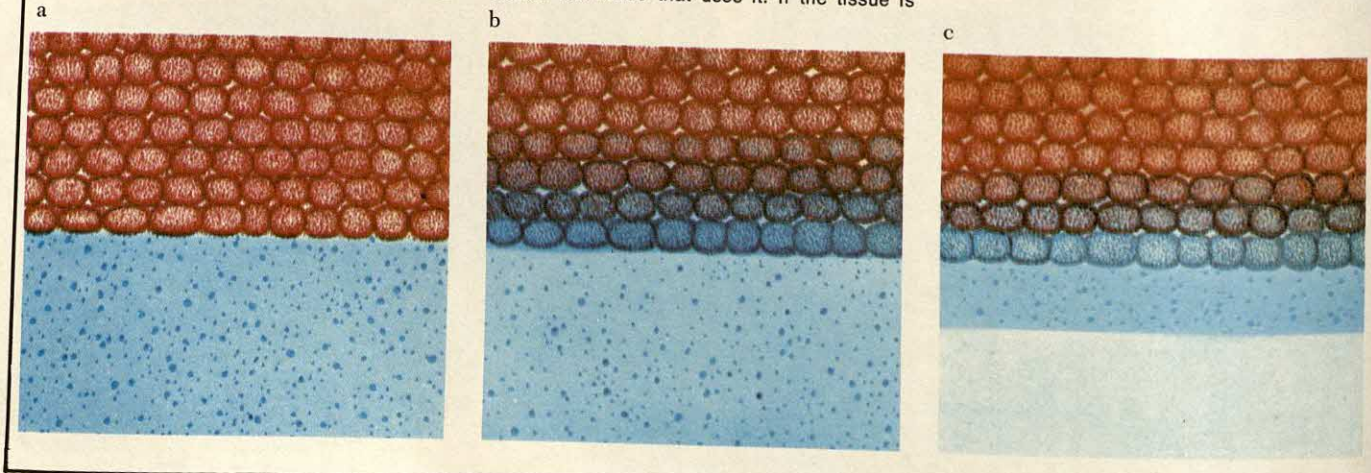
Animals are ultimately dependent on green plants for their food, because only these plants are able to photosynthesize or convert the energy of sunlight into forms that may be consumed and used by animals. Therefore, it is almost certain that plants preceded animals in making the transition to a land environment. As animals began to move onto the land, they probably continued to feed on aquatic organisms, at least initially. Eventually, however, as both plant and animal species diversified and proliferated on the land, animal dependence on the sea as a source of food diminished.

With few exceptions, living organisms require free oxygen to utilize their food. Practically every body of water contains a certain amount of dissolved oxygen. To satisfy their oxygen requirements, aquatic animals must have some means of obtaining this dissolved gas from their liquid surroundings. Many aquatic animals possess special tissues through which the dissolved oxygen may pass or diffuse. Such animals take the oxygen directly from the water into the tissues. If an animal so adapted emerges from the water, it is no longer able to use the oxygen, and it dies of asphyxiation.

It is possible, of course, for the oxygen consumption of an animal to be so low that it is able to leave the water for short periods of time, move around a little on land, and then reimmerse itself when the supply of oxygen in its tissues has been used up. This is analogous to what happens when a human dives under water. Although he can survive under water for a short time, he is not actually "adapted" to the aquatic environment; he must surface soon to replenish his oxygen supply—or he will die. Nevertheless, primitive creatures capable of making brief excursions onto dry land gradually evolved as time passed. Practically speaking, this

THE PROBLEM OF OXYGEN ABSORPTION— To absorb oxygen means to extract it from the environment so that it can be combined with nutrient substances, thereby releasing the energy stored in these substances. Because the amount of oxygen in both air and water is low, the problem of its absorption (that is, respiration) is highly complicated. An organ that extracts oxygen from the environment must be specifically adapted for this purpose. In every case such absorption takes place by dissolution of the gas in water, followed by diffusion into the living tissue. Dissolved substances such as oxygen tend to move from regions of high concentration to regions of low concentration.

The diffusion of oxygen from either seawater or fresh water into the tissues takes place in the following manner: first, the oxygen-poor tissue (Illustration 1a) is immersed in an oxygen-rich environment. From the aqueous environment with a high gas content, the oxygen diffuses into the tissue with a lower gas content (Illustration 1b). An equilibrium is thus established in which the oxygen content in the tissue is always below the oxygen content of the environment. The environment is always richer in oxygen than the tissue so that diffusion can continue. Because the oxygen is diffused from the water clinging to the tissue into the tissue itself, the water becomes oxygen-poor, but only near the tissue. From its unlimited reserve, the oxygen diffuses toward the tissue that uses it. If the tissue is covered by only a thin film of water with oxygen in solution, instead of being completely immersed in water, the oxygen is diffused from the atmospheric environment into the aquatic environment and then into the tissue (Illustration 1c). While before, the water-tissue interface served to slow or delay the movement of oxygen into the tissue, now both the air-water interface and the water-tissue interface act to delay the process. Therefore, in order to have efficient respiration by means of a tissue surface covered with a film of water, a large area of wet tissue is required. A respiratory system of this type is typical of many living things that populate the atmospheric environment.



is the historical essence of animal evolution.

The second step in the process of conquering the air environment involved the adaptation of organs for extracting oxygen from the air.

Today, many animals, including fish, take in oxygen through the skin as well as through specialized organs. The skin must be wet or moist, because the oxygen is dissolved in the layers of water in contact with the epidermis. Generally, only very small or very slender animals are able to acquire sufficient oxygen to sustain life by this means. A simple planarian, for example, has cells arranged in thin layers. It is able to obtain all the oxygen it needs by diffusion from the surrounding water. An eel, on the other hand, is much larger and more complex than a planarian, and it is able to satisfy only about half of its oxygen requirement by absorption through its skin.

It can be assumed that in the past, before air-breathing mechanisms were developed, absorption of oxygen through wet or moist skins was the means by which certain animals were able to survive their first incursions into the hostile air environment. These creatures must, therefore, have faced life on land that had a very wet climate, for the most part; otherwise, they could not have absorbed oxygen from the air. Later on, respiratory adaptations evolved into the lungs of today. In present-day lungs, the surfaces through which gaseous exchanges take place must be moist—a requirement that may be considered a holdover from the aquatic origins of life.

Support and locomotion were two related problems encountered by any animal moving from water to land. A land animal must be able to support its own weight without benefit of the buoyant or upward lifting force of water. According to Archimedes' principle, the body of any creature weighs less when it is immersed in water than when it is on land. The specific gravity of a living aquatic creature is about equal to that of water. Therefore, whatever appendages an aquatic animal possesses are not needed to support the animal in contact with the bottom. Indeed, these appendages often are scarcely strong enough to push the animal slowly forward.

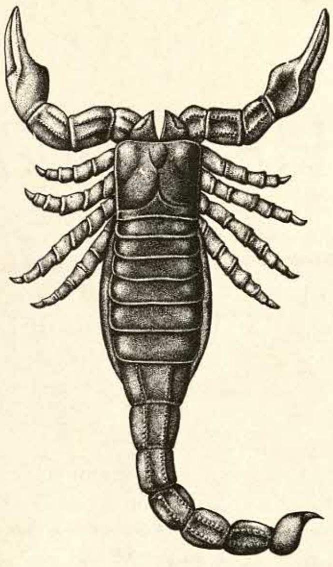
Locomotion is also affected by body shape and body structure. Under the water, the best form is that which allows for wriggling. However, wriggling along the surface of the land is not so efficient as wriggling through the water or along the ocean floor. An animal with legs, or other supporting structures that raise the body off the ground, is able to move with less friction and greater ease over land than an animal without such appendages. In the course of evolution, animals with strong, short legs became quite successful on land. Their limbs provided them with both support and locomotion. The absence of a buoyant medium, however, tended somewhat to limit the sizes of terrestrial animals.

In order to move through water, many aquatic animals push backward against the water with their appendages. This action, in accordance with Newton's third law of motion, produces an equal reaction in the opposite direction. The animal moves forward, much as a rowboat is propelled forward by the backward movement of oars. Similar locomotion, for the most part, is inefficient on land. Air, being a gas, is much more compressible than water and consequently offers much less resistance to motion. Only appendages such as the wings of a bird are adapted to move enough air backward to result in forward movement of the animal. Wings, of course, eventually appeared—but only long after a multitude of living species had populated the land.

SPECIALIZATION OF REPRODUCTION

The solution of the problem of respiration and the evolution of organs of locomotion were important aspects of the transition of life from water to land. There were, however, other problems to be confronted by living creatures in order for them to survive. The first and foremost problem was that of reproduction. In water, the liquid medium conserves the eggs and receives the young, enhancing their chances of survival as soon as they have been generated. Air, on the other hand, is hostile to new life, often leading to the desiccation or drying out of the eggs and to the resultant death of the immature organisms. Consequently, not only did adult forms have to adapt to an atmospheric environment; embryonic life also had to become adapted. The problem was first resolved by the amphibians: adults lived on land, but eggs were laid in the water, and the young spent the first part of their lives in that liquid medium. By necessity, then, amphibians were restricted to habitats adjacent to bodies of water.

The responses of animals to life on land were varied. Essentially they retained the reproductive forms developed in the water, modifying them in certain ways that were based on the necessities created by the new environment. Many animals continued to reproduce by means of eggs, but certain species developed eggs with hard or leathery shells. Such eggs could be laid on dry land, yet be protected from the desiccating effects of air. This adaptation permitted these species to survive and reproduce in habitats far removed from bodies of water.



2

THE MOST ANCIENT INHABITANT OF THE CONTINENTS—To this day *Palaeophonus nuntius*, of the Gotlandian area of Sweden, is the oldest recognized land animal. It belongs to a suborder of Protoscorpionida (scorpions); little is known about its way of life or its habits. Its appearance on the world scene marked the beginning of a new period in evolution.

The development of larval forms provided other ways in which immature animals could be defended against the harsh effects of the air. Larvae may be considered autonomous, imperfectly developed embryos that are protected either by returning to the water (as in the case of frogs), or by isolation in special structures such as the cocoons of certain insects, which enclose them in a quiescent state until they mature.

Eventually, higher forms of life such as the mammals evolved a still different means of reproduction and development. In most mammals, for instance, conception and gestation occur within the body of the mother. Here, too, the development of the embryo takes place in a liquid medium, thereby presenting strong additional evidence of a completely aquatic ancestral life.

As animal organisms spread across the land, occupying an enormous diversity of environmental niches, countless other adaptations evolved. Mechanisms for conserving moisture, regulating body temperature, ingesting and utilizing different kinds of foods—these are but a few of the adaptations that have been made through the long aeons since animal life first conquered the dry land.

THE DEVONIAN PERIOD | from lungfish to amphibians

The Devonian period was a time of great evolutionary progress, a period in which the fishes proliferated and diversified, becoming the dominant animals in the ocean. It was a period in which terrestrial plants thrived and the first forests appeared, and in which animals became firmly established on land.

The Devonian began about 400 million years ago and lasted for about 65 million years—a relatively short span of time compared with the 155 or so million years that had elapsed during the first three periods (Cambrian, Ordovician, and Silurian) of the Paleozoic era. Nevertheless, the evolutionary changes that occurred during the Devonian were so vital that they clearly distinguish it from the preceding periods and relate it to those that followed. The features of the Devonian were fundamentally the same as those that had marked the earlier periods, but certain structures became more highly developed and certain organisms became better adapted to various environments.

One noteworthy feature of the Devonian period was the appearance in vertebrates of an essential organ, the lung. This organ was significant because it was instrumental in the successful conquest of dry land by animals. The lung enabled an animal to remain on land for relatively long periods of time without having to return to the water to replenish its oxygen supply. The lung appeared initially as an auxiliary or emergency breathing apparatus in aquatic animals known as Dipnoi. These animals, true lungfishes, had a double respiratory system that enabled them to survive in both terrestrial and aquatic environs.

The appearance of limbs was another important feature of the Devonian, one intimately linked with the emergence of animal life from the water. Limbs permitted movement in a medium in which the body was no longer supported by the buoyancy of the water. The Dipnoi of the Devonian period had paired fins—structures analogous to rudimentary limbs. In all likelihood these animals inhabited swamps and streams that dried up during certain seasons, thereby forcing them into terrestrial life. They were able to survive on land precisely because they were equipped with double breathing systems, and they were able to move along the ground by means of their paired fins. For this reason, the Dipnoi are held to be the progenitors of the tetrapods, organisms whose locomotion is provided by means of two pairs of limbs. In the course of time, the tetrapods were to become highly evolved.

Well-defined geological phenomena also took place during the Devonian period. As yet, it is impossible to draw an exact map delineating the borders of the dry lands and of their evolution, but it is known precisely which large areas of the present-day continents were out of the water and which were submerged. It is known, for example, that the North At-

THE EARTH DURING THE DEVONIAN PERIOD —Although the changes that took place during the Devonian period were extensive enough to be represented by at least three maps, one for each epoch, the map shown projects only the middle Devonian period. Petrographic examination reveals that the formations were derived from the consolidation of detrital sediments of red sandstone in a subaquatic environment. The sediments, although spread over a vast area, are not particularly thick, as they would be if they had been produced by slow semiaquatic sedimentation. The great diffusion of red sandstone has led some scientists to call the North Atlantic continent of the Devonian period the Old Red Continent.

Central America, after undergoing great upheavals during the Cambrian and Silurian periods, eventually emerged from the sea to become a uniquely large continent, much larger than it is today. Furthermore, according to some scientists, South America was still linked to Africa by a bridge across the Atlantic. The sea spread over North America, and the Rocky Mountain zone, especially, sank with the subsiding belt (geosyncline) of the Cordillera. Short mountain chains and volcanoes broke the surface in several places.

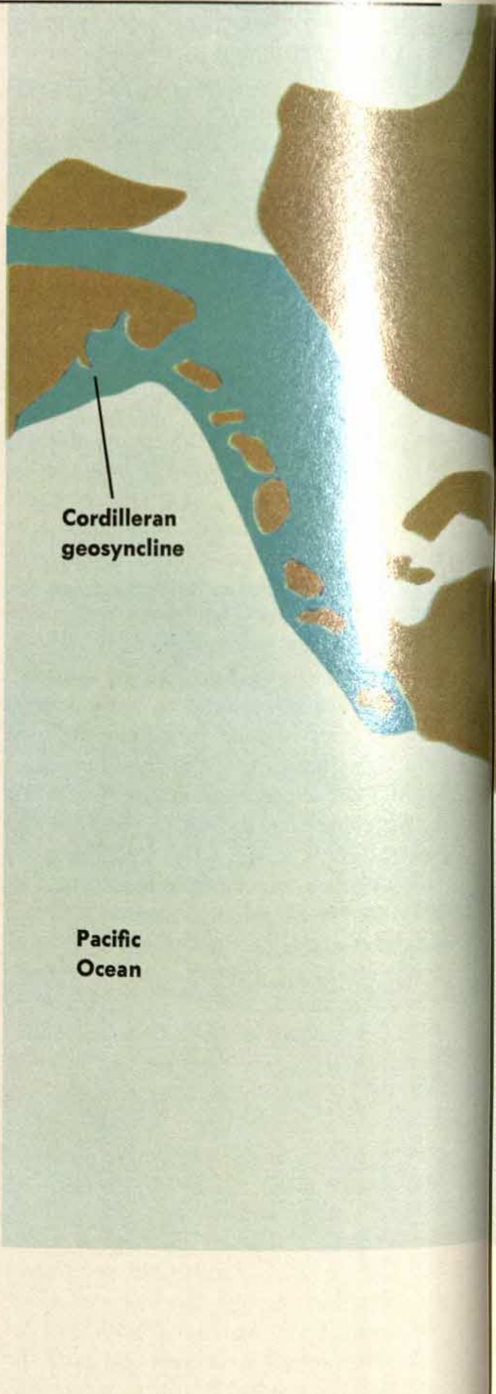
In Scandinavia, a low mountain chain arose, but was quickly eroded, giving way to a slight folding and a low sea plain.

Mountain-building convulsions (the Caledonian orogeny) came to an end, and Europe was invaded by the sea. A great geosyncline formed the present Mediterranean Basin, reaching as far as the Baltic Sea of today. The Tethyan Seaway stretched from this geosyncline, with shallower seas, as far as Asia where it again opened out into the Indian Ocean and then, by another expanse of sea, extended into the Pacific Ocean. The most interesting region, however, was that of Asia east of the Urals and north of the present peninsula of Saudi Arabia and India. Here was located the great geosyncline of the Urals, which connected the Indian Ocean and the Pacific with the Arctic.

Eastern Asia, near its borders with North America, was also marked by an enormous new geosyncline. Of recent formation, it was accompanied by warping and volcanism.

Australia, connected with Asia by the Equinoctia continent, was still flanked by two deep geosynclines.

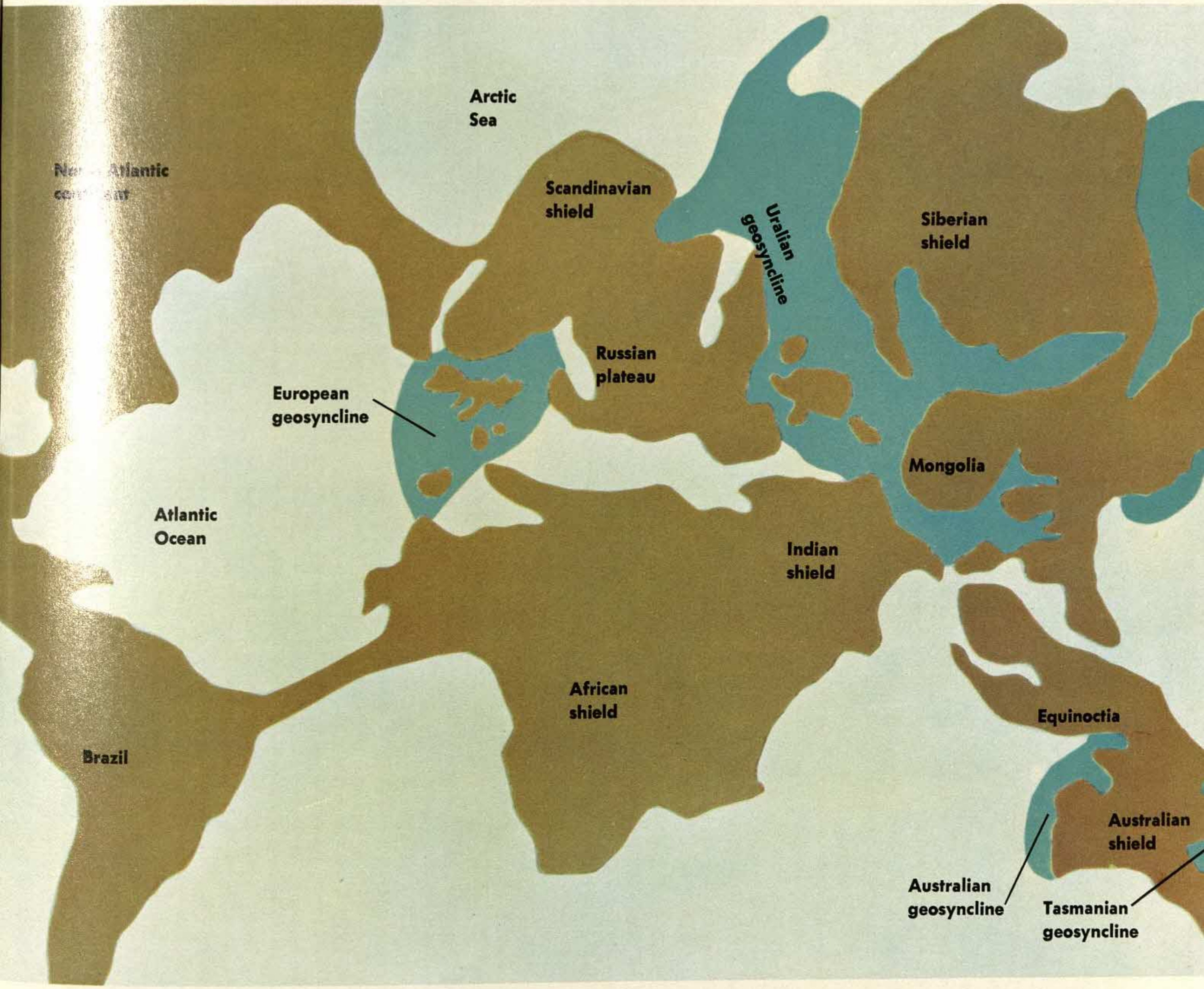
Seen from above, some continents would have appeared covered with vegetation.



lantic continent still existed during the Devonian, linking North America and northern Europe by means of a great land bridge.

At the beginning of the Devonian the continents were at their maximum size; at no time since has there been so much dry land on the Earth. As time passed, more of the land became submerged and the borders of the landmasses shifted, making them entirely different from the continents of today. In particular, the Caledonian chain, which had risen during the Silurian period, sank under the sea; this was one of the major movements of the Earth during this period. Toward the end of the Devonian, the climates became colder and glaciation took place. Proof of this change is found in Africa near the Cape of Good Hope, where clearly exposed glacial sediments have been left.

Some of the world's most celebrated landscapes come from weathered Devonian rocks. Included are the best of north Rhineland scenery in Germany, the Ardennes and Brest harbor in France, the Catskill Mountains of New York State, and the south coast of Devonshire in England, whence comes the name *Devonian*.



FAUNA OF THE DEVONIAN PERIOD | the age of fish

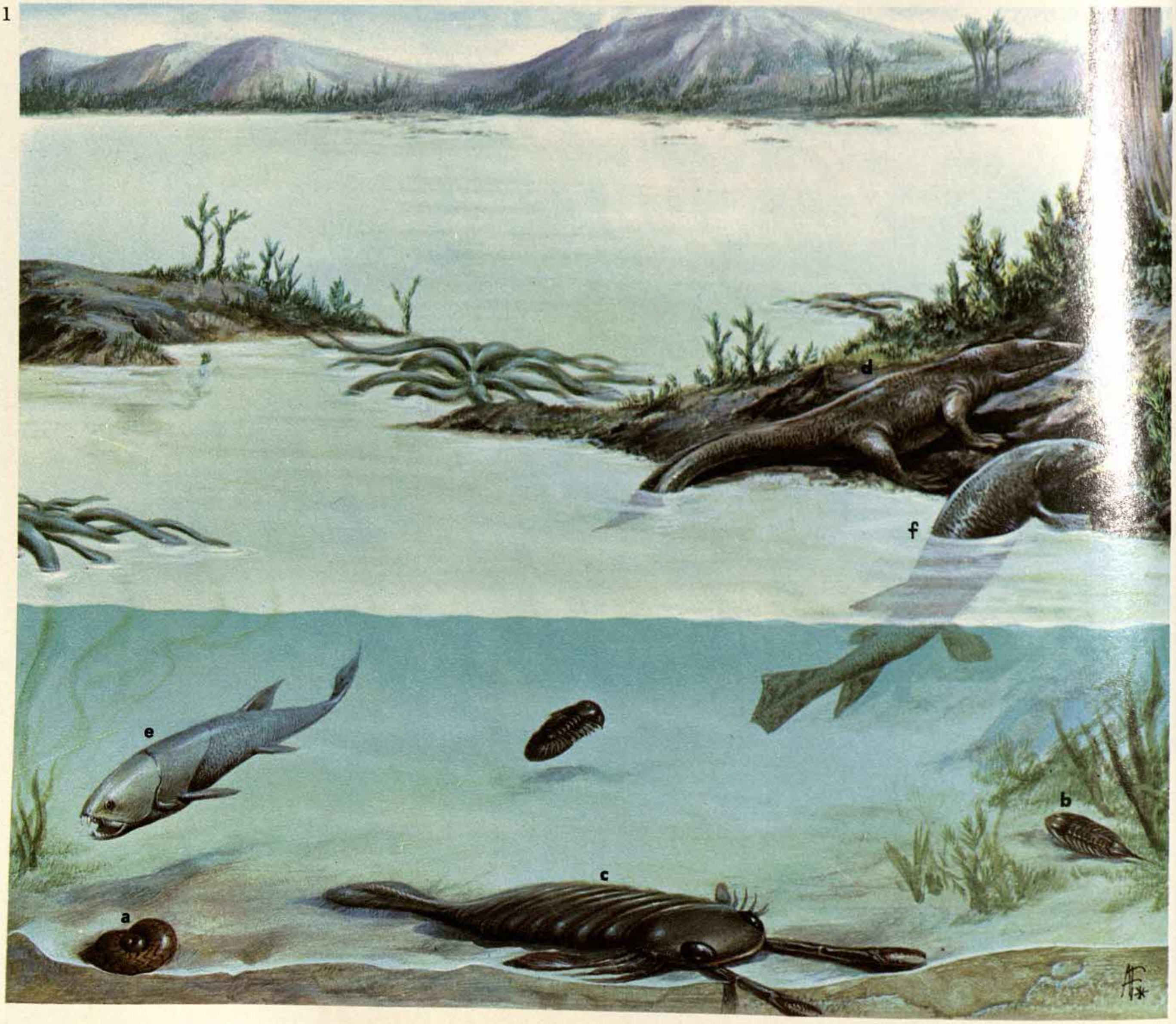
THE DEVONIAN SCENE—During the Silurian period, which immediately preceded the Devonian period, a few living forms emerged from the water and colonized on land, but most remained in the sea. Among the marine organisms that still existed in the Devonian were the cephalopods known as ammonites (Illustration 1a), the trilobites (Illustration 1b), and the eurypterids (Illustration 1c), both arthropods. The trilobites were most numerous during the Cambrian and the Ordovician periods; they were still abundant during the Devonian but became extinct by the end of the Permian. The eurypterids lived at the same time as the trilobites and became extinct at the same time. *Pterygotus buffaloensis* (Illustration 1c) was one of the largest invertebrates ever to live—almost 3 m (about 10 ft).

Among the vertebrates of the Devonian were the placoderms, crossopterygians, and the early amphibians. The placoderms (Illustration 1e) were the first jawed fishes. They first appeared late in the Silurian period and reached their greatest numbers during the Devonian. The fish shown here is Coccosteus; its head is covered by an armor of bony plates. Some placoderms were fearsome carnivorous fish that reached lengths of almost 10 m (about 30 ft). By the end of the Devonian, most of the placoderms were extinct; the last died during the Permian.

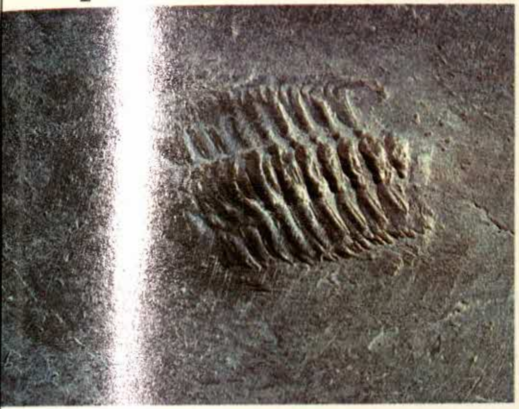
The lobe-finned fish or crossopterygians (Illustration 1f) first appeared during the middle of the Devonian. These fish were unusual in having muscles that extended into the fins and so were better able to control the movements of the fins. Lobe-finned fish also had lungs and were able to breathe air. Among their living descendants are the lungfishes that inhabit streams and ponds in South America, Australia, and Africa. Some crossopterygians gave rise to a completely new group, the amphibians.

Ichthyostega eigeli (Illustration 1d) was an early amphibian that appeared late in the Devonian. It was an air-breathing animal at home on land, although not independent of water as are present-day amphibians. However, an important step had been taken in the colonization of the land, for the amphibians later gave rise to the reptiles—the ancestors of mammals and birds.

1



2



TRILOBITES—The trilobites appeared at the beginning of the Cambrian period—the earliest division of the Paleozoic era. They developed rapidly during the Silurian period, disappearing completely at the end of the Devonian, the period succeeding the Silurian.

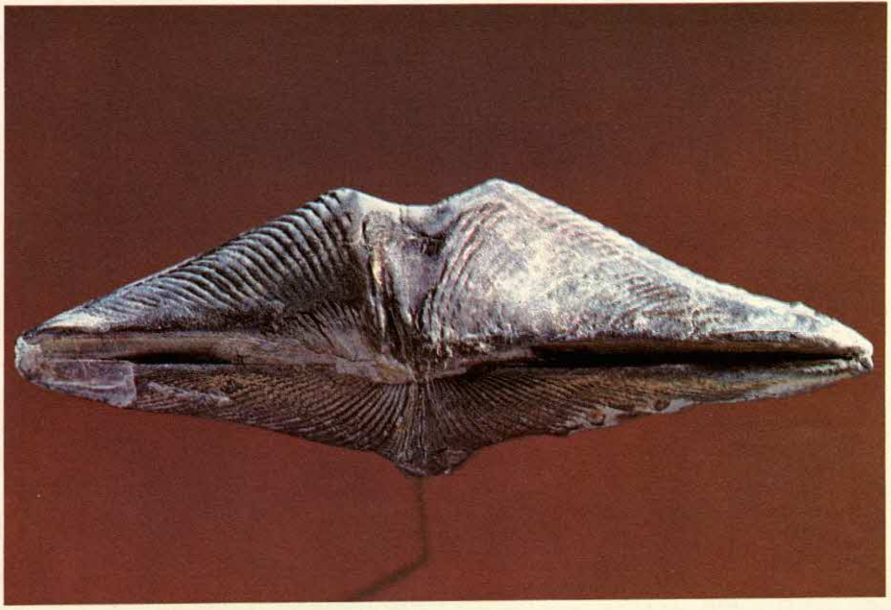
This illustration shows an imperfectly preserved Devonian trilobite of the genus *Phacops*, pyritized on slate.

TOWARD LARGER FORMS—The Mollusca is one of the largest and most important phyla of invertebrate animals; it includes snails, slugs, clams, oysters, mussels, squids, octopuses, and others. Extremely large mollusks lived during the Devonian period.

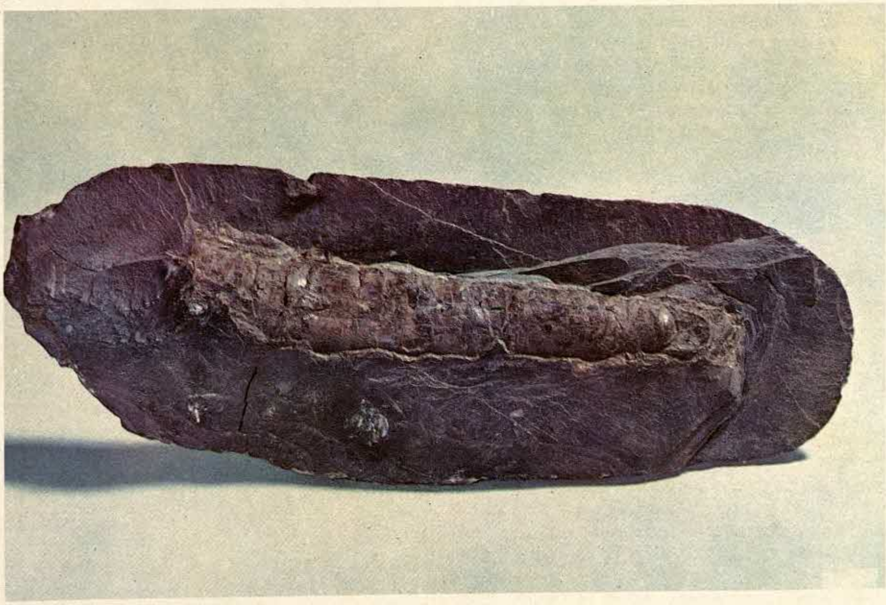
Illustration 3a is *Cyrtospirifer verneuili*, a Devonian brachiopod 10 cm (about 4 in.) wide and 4 cm (about 1.6 in.) thick.

The mollusk of the genus *Orthoceras* (Illustration 3b) is the ancestor of the ammonites, which had markedly spiral shapes. This specimen was found in the valley of Ansdruck in Germany and is preserved in slate. *Orthoceras* had not yet acquired a spiral shape.

3a



3b



The Devonian period is a geological age that began about 400 million years ago and lasted about 60 million years. It derives its name from Devon, England, where rocks from this period were first studied. Devonian rock formations are also found in eastern North America and parts of the major mountain regions of North America, as well as in parts of Europe.

The Devonian is sometimes called the age of fish because of the variety and abundance of fossil fish found from that age. More than one hundred species have been discovered in North America alone.

Sediments and fossils from the Devonian reveal that the climate was mild, and that lands in what is now the North Atlantic contained bodies of fresh water and primitive vegetation. The sea spread widely over what are today's continents.

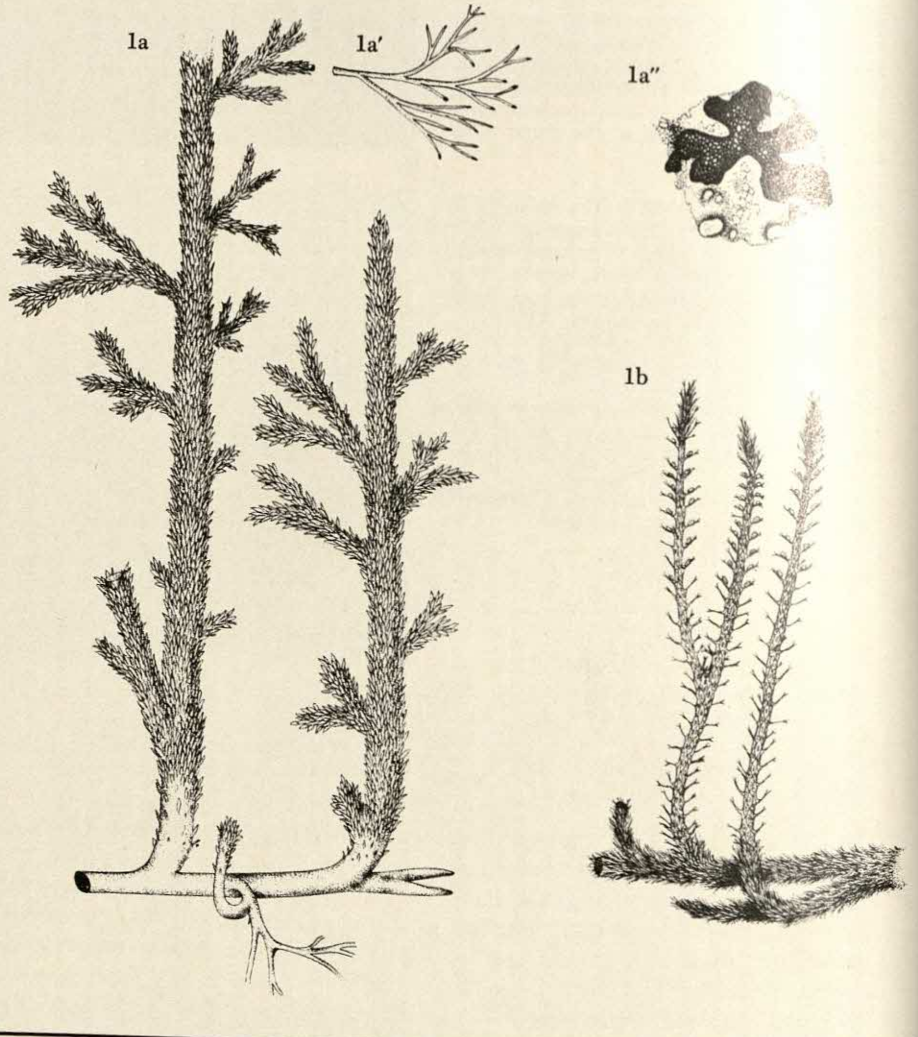
During the latter part of the Devonian period, the first four-footed vertebrates evolved from the fish and began the conquest of land. Species at this time proliferated for two reasons: the freshwater lakes favored their isolation and protection; and the emergence of dry land spurred the evolutionary process of adaptation and survival.

THE DEVONIAN SCENE | modern life-forms foreshadowed

Each geological era, it seems, can be characterized by some outstanding step in evolution. The Devonian period—which began about 400 million years ago and ended about 50 million years later—was the time when the land was becoming rapidly covered by plant life, and the early amphibians were taking their first steps on land. To be sure, plants had already spread onto the land, and there is some evidence that they may have been on land during the Cambrian period at least 550 million years ago; however, a great diversification of plants seems to have occurred during the Devonian period. This is not surprising, for a new habitat—dry land—had become available, and new species evolved that could live in the various ecological niches that the land provided. By the end of the Devonian period at least some members of each of the subdivisions of the vascular plants were present.

Animals depend on plants for their food, and so any new area is invaded first by plants and later by animals. It was only during the Devonian that the first vertebrates—the air-breathing fish and the amphibians—came on land. The real diversification of terrestrial vertebrates occurred in periods following the Devonian. Insects and other terrestrial invertebrates also experienced great diversification in later periods.

The seas of the Devonian period held a wide variety of marine invertebrates and some vertebrates. Among the latter were the jawless fishes, the armored placoderm fishes, and the air-breathing crossopterygians. Because of this abundance of fish, the Devonian period is sometimes called "The Age of Fishes."



EARLY LAND PLANTS—*Asteroxylon mackiei* (Illustration 1a) was a land plant of the Devonian period. It belonged to the order Psilophytales, which contained very simple vascular plants. *Asteroxylon mackiei* was small with aerial stems about 0.5 m (about 1.5 ft) in height and covered by small, scalelike leaves. The stems rose from naked horizontal underground stems, or rhizomes. Spores were produced in sporangia that were borne at the tips of slender, leafless branches (1a′). A cross section of the vascular tissue (1a″) shows xylem (water-conducting tissue), which appears dark, and phloem (food-conducting tissue), which appears light. The vascular tissue formed a central core in the stems.

Protolepidodendron scharyanum (Illustration 1b) was one of the earliest members of the class Lycopsida (club mosses). It had a branched rhizome from which arose aerial stems that grew 20 to 30 cm (about 8 to 12 in.) tall; both were covered by minute leaves. The leaves were branched at the tip, and their bases were enlarged into leaf cushions; these were arranged in vertical rows that can be seen in tangential sections cut near the exterior of the stem (Illustration 1b′).

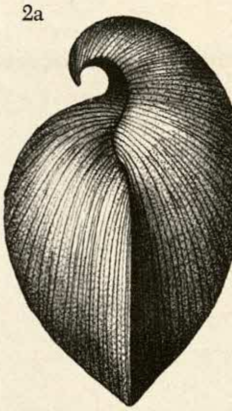
Several species of *Archaeopteris* were common during the Devonian period. Illustration 1c shows part of a leaflet of *Archaeopteris hibernica.* The leaves were pinnately compound and had several leaflets, each of which was divided into smaller leaflets. These ferns had large leaves, some of which were as much as 1 m (about 3 ft) long. The plants resembled shrubs or small trees.

DEVONIAN SHELLS—Animals having hard parts (like shells) are more likely to leave fossils than animals with only soft parts. Shown here are the fossils of two lamp shells (phylum Brachiopoda), *Stringocephalus burtini* (Illustration 2a) and *Uncites gryphus* (Illustration 2b), and two cephalopods, *Anarcestes subnautilinus* (Illustration 2c), and *Manticoceras intumescens* (Illustration 2d).

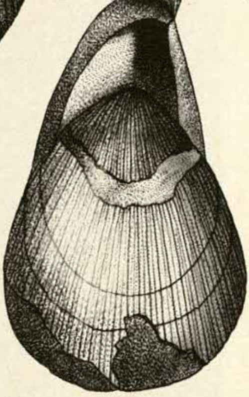
Lamp shells superficially resemble clams and oysters but are not related to them. The two valves of a clamshell lie to the right and left sides of the animal; those of lamp shells are upper and lower valves.

Some cephalopods of the Devonian period had coiled shells resembling those of snails. The shell was divided into several chambers. The curved lines on the surfaces of the shells indicate the locations of the internal walls.

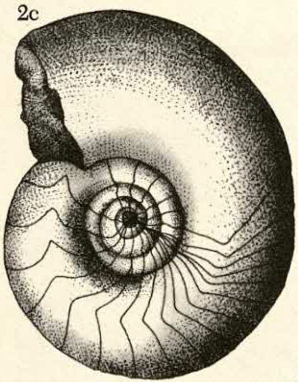
2a



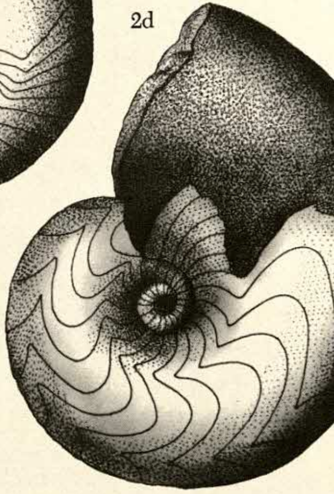
2b



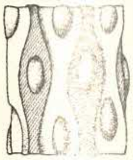
2c



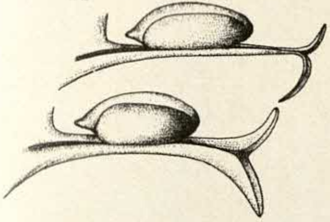
2d



1b'



1b'''



1b

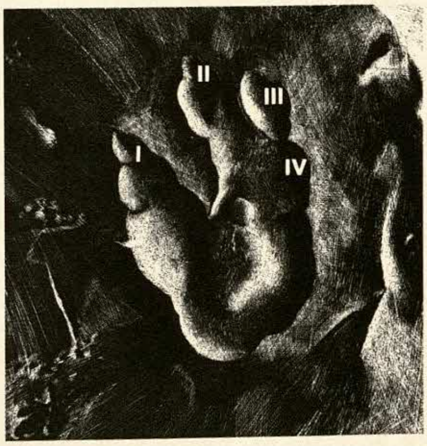
1c

THE FIRST TRACKS—Imprints of aquatic animals can be found in rocks dating back a billion years. The oldest of these traces are those of annelid worms. The tracks of aquatic animals were rarely preserved as fossils because the tracks were made in very soft materials (marls and clays) underwater and were, therefore, rapidly destroyed by the constant motion of water.

In the case of imprints of semiaquatic forms the difficulties of preservation were even greater; nevertheless, under particular circumstances imprints were well preserved. For example, where imprints occurred in still soft clay that later dried and was covered by a deposit before becoming inundated with water, the clay hardened and preserved the imprints.

The illustration shows the first known footprint of a terrestrial animal, one of the first amphibians, *Thinopus antiquus.* The print is mute testimony to the fact that aquatic animals had recently moved to land and that they already had limbs. The foot is quite different from the ambulacral extremities of the highly developed trilobites—two toes are clearly separated, the third is quite sketchy, and a fourth barely juts out laterally. Many other modern characteristics of life were foreshadowed during the Devonian period.

3



THE PLANT KINGDOM | more than 300,000 species

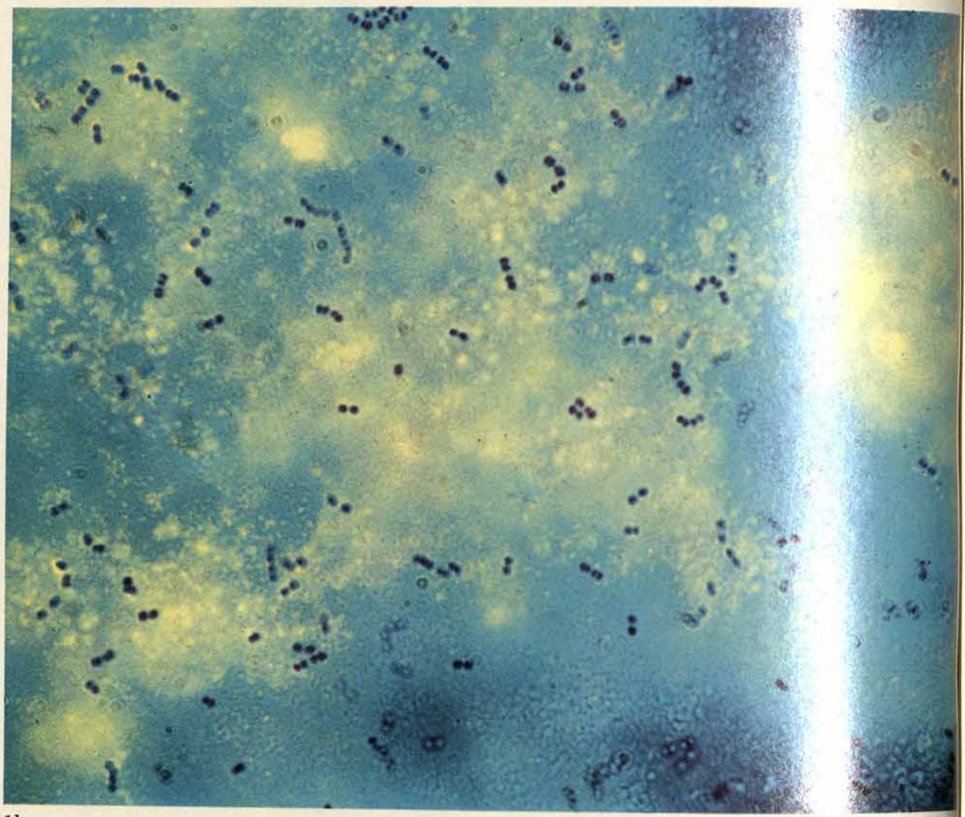
Plants, like animals, live in all habitable places of the Earth. Fossils of very simple plants resembling present-day bacteria have been found in rocks estimated to be more than 3 billion years old. Since the time these minute organisms lived, plants have evolved into types capable of surviving in the sea, in fresh water, and on land.

In the sea, where life is believed to have originated, aquatic plants have little need for special water-absorbing organs, water-conducting tissues, or water-conserving adaptations. The earliest plants,

---

THE PLANT KINGDOM TODAY—Bacteria (Illustration 1a), the most primitive of plants, are single-celled and microscopic. With a few exceptions, they lack chlorophyll and are unable to manufacture food. Bacteria, fungi, and algae are nonvascular plants sometimes classified in a larger group, Thallophyta. Algae (Illustration 1b) are thallophytes that have chlorophyll but, like other thallophytes, lack roots, stems, and leaves. Algae vary in size from a single microscopic cell to large seaweeds that grow to a length of 50 m (about 160 ft). Seaweeds, which grow along rocky coastlines, are supported only by water and not by their own tissues; when the tide goes out they are left draped over the rocks. Mushrooms (Illustration 1c), like other fungi and bacteria, are nonphotosynthetic. They live primarily on dead organic material in the soil. A few fungi are aquatic, but most of them, like these mushrooms, are terrestrial. Lichens (Illustration 1d) are plants that consist of both a fungus and an alga. They are extremely resistant plants and can grow on bare rock that would not support any other vegetation. Mosses (Illustration 1e), small terrestrial plants that have no roots, stems, or leaves, are believed to have evolved from green algae, for they have the same kinds of photosynthetic pigments as green algae. Ferns (Illustration 1f), together with coniferous and flowering plants, belong to the Pteropsida, the members of which are believed to have descended from green algae. Their photosynthetic pigments are the same as those of the green algae and the mosses. The pteropsids have roots, stems, and leaves. Ferns produce spores on their leaves, but they do not form seeds. Cone-bearing plants, or gymnosperms (Illustration 1g), bear their seeds on the scales of which their cones are composed. Flowering plants, or angiosperms (Illustration 1h), produce their seeds in fruits that develop after the flowers are pollinated.

1a



1b

1c

therefore, were fairly simple ones—bacteria and algae consisting of only one or a few cells. Each cell was capable of absorbing some of the water in which it lived. Multicellular forms also developed, but they showed relatively little differentiation into different types of tissues or organs; their internal cells were similar to the external cells from which they could easily receive all the water they required.

By far the most important of the aquatic plants are the algae. These plants have no roots, stems, or leaves; however, they do have chlorophyll, and they manufacture food by the process of photosynthesis. Such self-sufficient plants are called autotrophs. Marine animals are dependent on them for their food supply.

The oldest fossil algae, from the Precambrian era, are at least 2 billion years old. These are the blue-green algae (Cyanophyta). Fossils of green algae (Chlorophyta) have been found in de-

1e

1f

1g

1d

1h

posits laid down about 450 million years ago during the Ordovician period, and evidence exists that green algae may be much older, perhaps as much as 2 billion years. Other algae include the red algae (Rhodophyta), which lived in the Ordovician period, and the brown algae (Phaeophyta), which have existed since the Devonian period, almost 400 million years ago. Diatoms (Chrysophyta) and dinoflagellates (Pyrrhophyta) lived at least as long ago as the early part of the Jurassic period, nearly 200 million years ago. Members of all these groups exist today, and the diatoms and dinoflagellates, both of which are single-celled algae, are important photosynthetic water plants.

When plants first invaded the land, they encountered a new environment. Except for low-lying, swampy areas, much of the land is dry for long periods, and plants living there are exposed to drying winds. Land plants, therefore, must be adapted to living under conditions unlike those of the sea. Most of the land plants belong to two main groups that probably evolved separately from green algae. One group is a small one that includes the mosses and liverworts (Bryophyta). The other group includes all the vascular plants (Tracheophyta): among them are the psilopsids (Psilopsida); club mosses (Lycopsida); scouring rushes or horsetails (Sphenopsida); and the ferns, cone-bearing plants, and flowering plants (Pteropsida).

Most bryophytes and vascular plants have at least some parts that stand upright above the soil. In the case of large trees, some parts may reach as much as 100 m (about 300 ft) or more above the ground. Because the aerial parts are far distant from the soil that is the only fairly reliable source of water, these plants require special water-absorbing organs. The bryophytes have rhizoids, rather delicate rootlike structures that are only one cell wide and usually only one or a few cells long. The vascular plants have roots that are relatively large structures many cells thick and often quite sturdy. Both rhizoids and roots help to anchor the plants in soil.

Because water is absorbed by only one part of the plant, most bryophytes and vascular plants require special water-conducting tissues that can transport water from the rhizoids or roots to the aerial parts of the plant. The water-conducting tissues of the bryophytes are rather poorly developed, and so these plants have always remained small. Among the vascular plants, however, the roots, stems, leaves, and other organs are equipped with veins, or vascular bundles. The veins consist of two main types of tissue: xylem, which conducts water upward; and phloem, which conducts food both upward and downward in the plant. From an evolutionary point of view, vascular plants are more successful than the bryophytes; large numbers of vascular plants have managed to adapt to many different types of habitats, including deserts. The bryophytes, by contrast, consist of relatively few species, nearly all of which are confined to moist places.

In the class Pteropsida of the vascular plants, the conifers and flowering plants encompass all the major crop plants of the world. Man's existence depends on the tracheophytes. The general structure of the vascular plant is remarkably similar in the many groups of primitive tracheids, suggesting a common ancestral stock. The alternation of generations is noteworthy in vascular plants. The sporophyte generation, which begins with the fertilized egg, is the dominant phase of the life cycle. The gametophyte generation begins from a spore, which is the product of the reductional divisions in a sporangium of the sporophyte. In ferns and horsetails, the spore germinates on soil or humus and becomes a small green free-living plant. In the flowering plants, the gametophyte generations are represented by the female gametophyte within the immature seed (ovule) and by the male gametophyte (pollen grain).

Both bryophytes and vascular plants have an epidermis covered by cutin, a substance impermeable to water. Cutin prevents evaporation of water from the epidermis and helps to conserve water within the plant. In general, the cutin is thickest on desert plants and thinnest on those that grow where water is plentiful (many aquatic plants have no cutin). Stems and roots more than one year old are usually covered by cork, a tissue that contains suberin, another substance impermeable to water.

CLASSIFICATION OF THE PLANT KINGDOM

Phylum or Division

1. Chlorophyta—green algae
2. Euglenophyta—euglenoid algae
3. Chrysophyta—yellow-green algae, golden brown algae, and diatoms
4. Pyrrhophyta—dinoflagellates, desmokonts
5. Phaeophyta—brown algae
6. Cyanophyta—blue-green algae
7. Rhodophyta—red algae
8. Schizomycota—bacteria
9. Myxomycota—slime molds
10. Eumycota—true fungi
11. Bryophyta—mosses and liverworts
12. Tracheophyta—vascular plants
    - Class Psilopsida—psilopsids
    - Class Lycopsida—club mosses
    - Class Sphenopsida—horsetails
    - Class Pteropsida—ferns, cone-bearing plants, and flowering plants

THE EARLY EVOLUTION OF TERRESTRIAL PLANTS

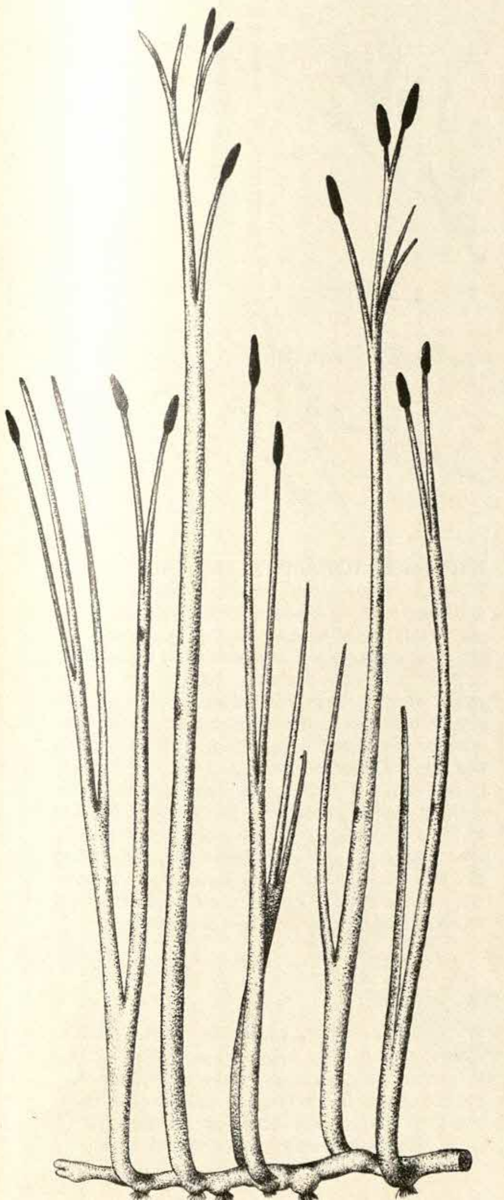
from ancient bacteria to primitive trees

The conquest of the land by plants and animals was a long and difficult process, involving many obstacles. Historically speaking, an aqueous environment has always been the most favorable to life, for it directly supplies the cells of organisms with their essential nourishment and their indispensable oxygen.

Another advantage offered by an aqueous environment is that organisms—even large ones—do not require strong, rigid structures to support their weight. In accordance with Archimedes' principle, any body, (organic or inorganic) weighs less in water than out of water; consequently, the buoyancy of the water makes unnecessary the development of sturdy supporting structures.

In a land environment, life must exist without these advantages. Plants, for example, must be equipped with structures that permit them to obtain water, minerals, and carbon dioxide, and with structures to support themselves. Therefore, while it is not absolutely necessary for aquatic plants to be solidly anchored to the floor of a body of water—even though this may be a help to them—terrestrial plants require some sort of root structure

Plants underwent a great specialization in their transition from an aquatic to a terrestrial life. In the study of evolution, it must be remembered that the greatest strides were made when life first began.



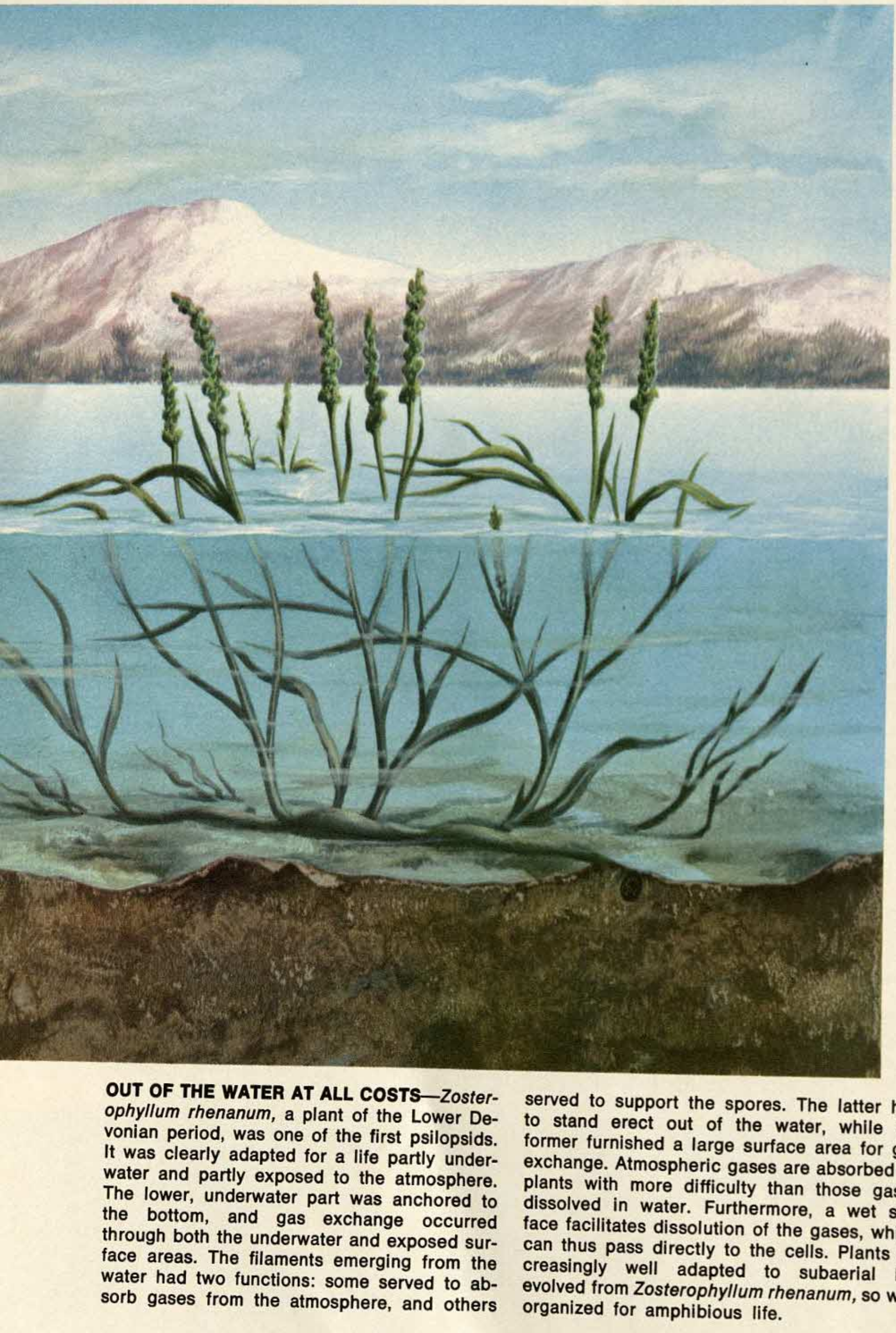
LIFE OUT OF THE WATER—The transition of plants from water to land entailed many problems. Plants had to develop new organs to acquire carbon dioxide from the atmosphere and water and minerals from the soil. Moreover, the soil in which plants had to take root was as barren as the surface of a lava flow. Humus, which now is recognized as being of great importance to plant growth, was nonexistent because humus is produced by the decomposition of organic remains.

The earliest plants had no leaves; these structures did not appear for a considerable length of time. However, by a phenomenon of evolutionary convergence, as soon as the plants had made the transition to a terrestrial existence, some of their parts came to have a form similar to that of true leaves, thus permitting the development of the functions peculiar to leaves.

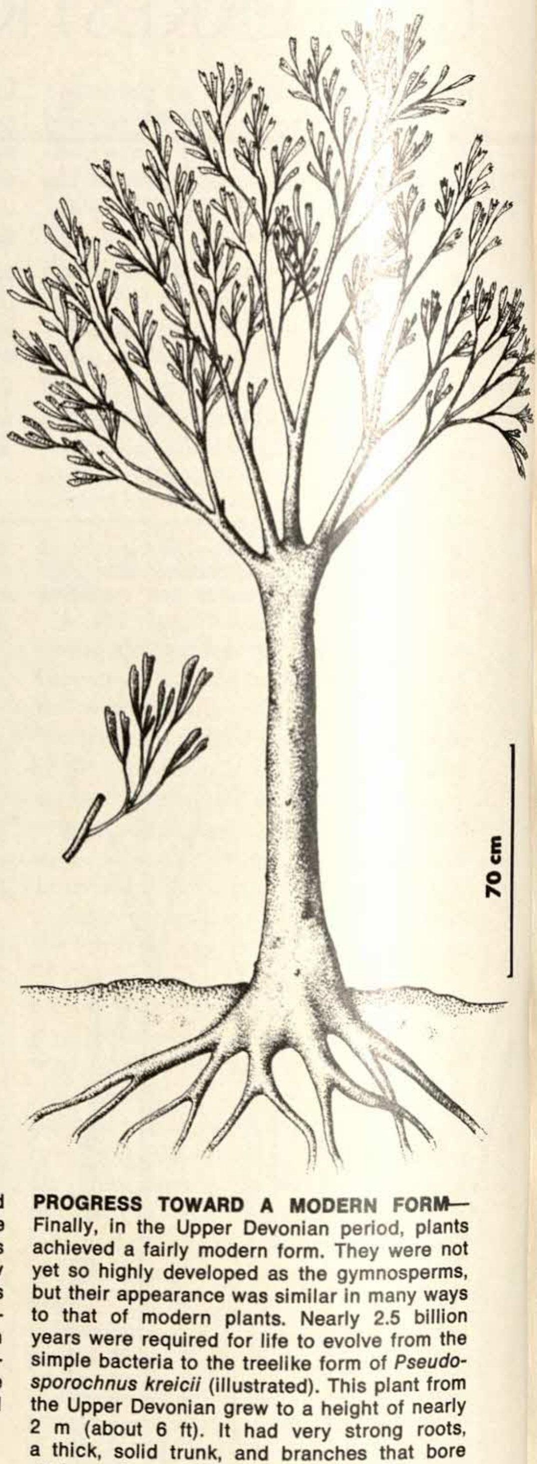
This drawing depicts *Rhinia major,* a psilopsid of the Middle Devonian period and one of the first plants to appear on land. The plant consisted of a number of long slender cylinders or filaments branching off from a stem that ran along the ground; every sterile filament ended in a point, while every fertile one was capped with an organ containing spores. These plants had no true roots; instead, a structure resembling a rhizome, or underground stem, anchored the plant to the ground, thus solving a vital problem of the terrestrial plant.

INCREASING COMPLEXITY—The branching or ramification of algae filaments was a feature which continued to evolve. *Thamnocladus clarkei* (illustrated), of the Upper Devonian, had much more complex and numerous ramifications than earlier algae, and had a larger area through which diffusion could occur. This adaptation enabled the plant to increase its mass and maintain a speed of development independent of its size.

ALWAYS A WATER PLANT—From the simple forms of the algae evolved the plants that succeeded in conquering the land. However, the algae themselves have remained aquatic organisms up to the present day. Nothing more highly developed has been derived from them, although the number of known species has increased enormously. This photograph reveals a large number of *Bythotrephis gracilis* embedded in a Silurian rock. These macroscopic algae were quite highly developed.



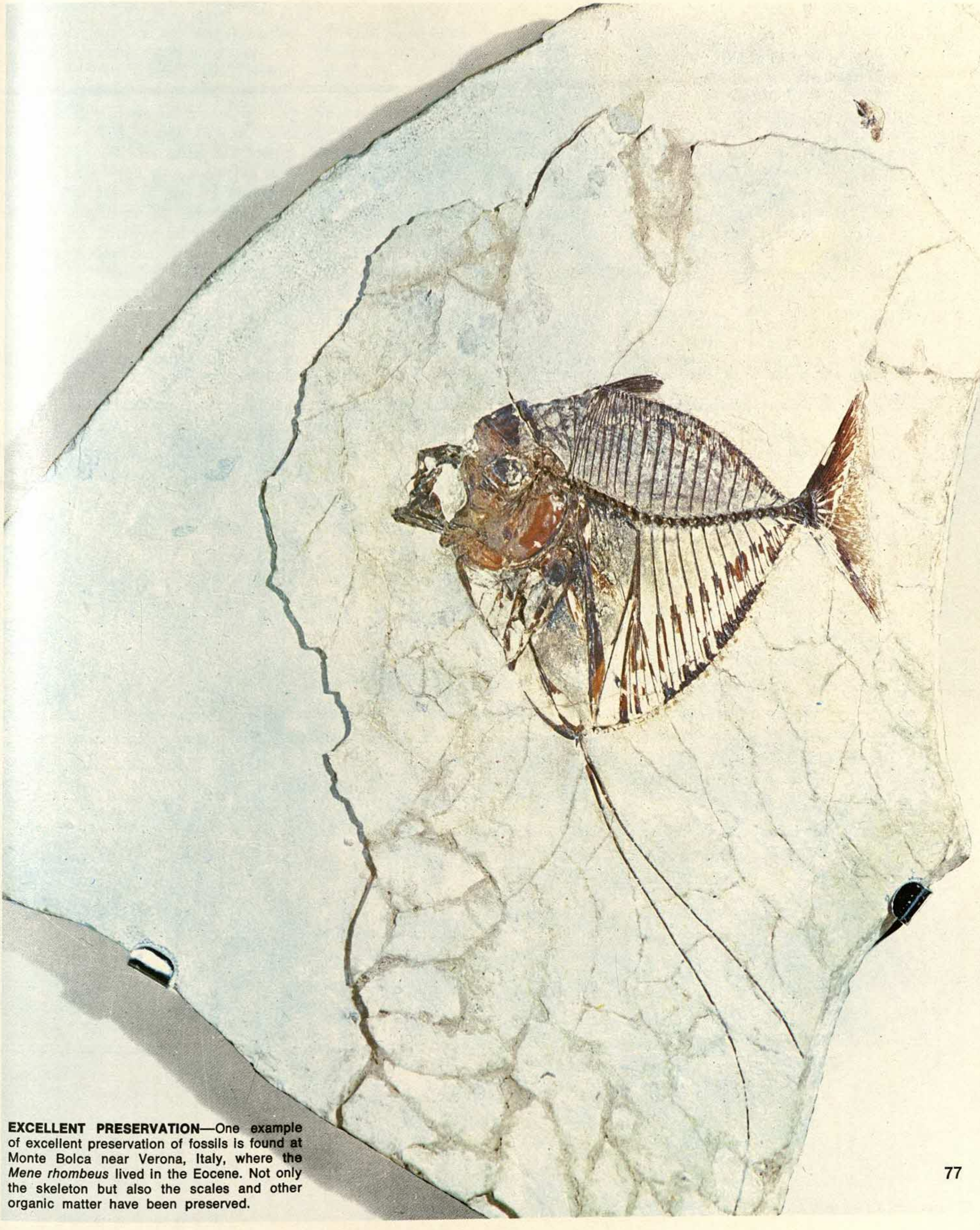
OUT OF THE WATER AT ALL COSTS—*Zosterophyllum rhenanum,* a plant of the Lower Devonian period, was one of the first psilopsids. It was clearly adapted for a life partly underwater and partly exposed to the atmosphere. The lower, underwater part was anchored to the bottom, and gas exchange occurred through both the underwater and exposed surface areas. The filaments emerging from the water had two functions: some served to absorb gases from the atmosphere, and others served to support the spores. The latter had to stand erect out of the water, while the former furnished a large surface area for gas exchange. Atmospheric gases are absorbed by plants with more difficulty than those gases dissolved in water. Furthermore, a wet surface facilitates dissolution of the gases, which can thus pass directly to the cells. Plants increasingly well adapted to subaerial life evolved from *Zosterophyllum rhenanum,* so well organized for amphibious life.



PROGRESS TOWARD A MODERN FORM—Finally, in the Upper Devonian period, plants achieved a fairly modern form. They were not yet so highly developed as the gymnosperms, but their appearance was similar in many ways to that of modern plants. Nearly 2.5 billion years were required for life to evolve from the simple bacteria to the treelike form of *Pseudosporochnus kreicii* (illustrated). This plant from the Upper Devonian grew to a height of nearly 2 m (about 6 ft). It had very strong roots, a thick, solid trunk, and branches that bore at the ends structures resembling true leaves. Plants such as this one formed forests during the Devonian. In the meantime, the lycopods were evolving, reaching their highest point of development during the Carboniferous.

THE ORIGIN OF THE VERTEBRATES

1a



EXCELLENT PRESERVATION—One example of excellent preservation of fossils is found at Monte Bolca near Verona, Italy, where the *Mene rhombeus* lived in the Eocene. Not only the skeleton but also the scales and other organic matter have been preserved.

One of the great unsolved mysteries of evolution is the origin of the vertebrates, which constitute one of the two main groups into which the animal kingdom is divided (the other group consists of invertebrates). Both groups are so ancient that fossils of their earliest members have not yet been found.

The oldest vertebrate fossils are those of some primitive eel-like fish resembling the lampreys of today. These ancient fish lived almost 500 million years ago in the Ordovician period of the Paleozoic era. These fossils are incomplete, but the presence of bone in some of them clearly indicates that they are vertebrates. Unlike most vertebrates they had no jaws.

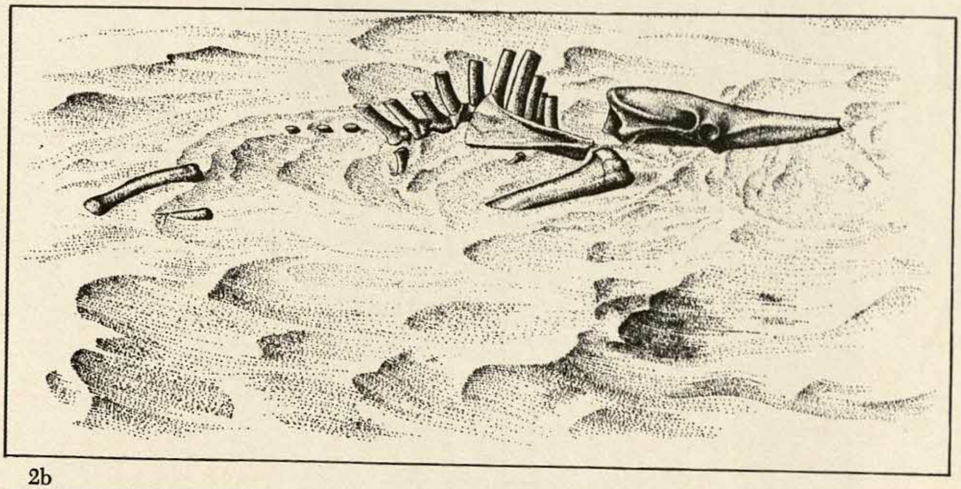
The existence of any organism as complex as a vertebrate implies that a long period of evolution preceded it. For this reason it is thought that the first simple vertebrates may have evolved in the Cambrian period which began about 600 million years ago and ended some 100 million years later. But the fossil record of this period gives no information, and paleontologists can only speculate about the exact time that vertebrates first appeared on the Earth.

About 420 million years ago, in the Silurian period, the placoderms, armored fish with jaws, appeared; these are now extinct. The major vertebrate groups that exist today began to appear early in the Devonian period, at least 400 million years ago, when the cartilaginous fishes and the bony fishes lived. Amphibians, reptiles, mammals, and birds appeared in successively later periods.

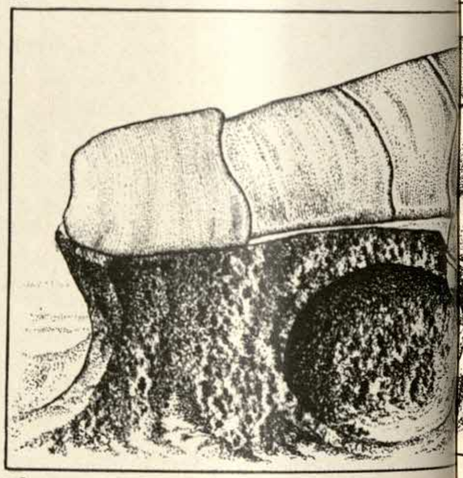
EXTRACTION FROM THE GROUND—Fossil remains of large creatures are not always in one piece. Their various parts often break off from each other, and so it is necessary to find some way of putting the whole skeleton together again without losing any of its fragments. The greatest difficulty is that of recovering any soft parts that may have been preserved.

When fossil remains are exposed by erosion or by excavation (Illustration 2a), the excavation is continued carefully to determine the extent of the remains (Illustration 2b). The bones are coated with chemicals to preserve them, and they are covered with a plaster cast

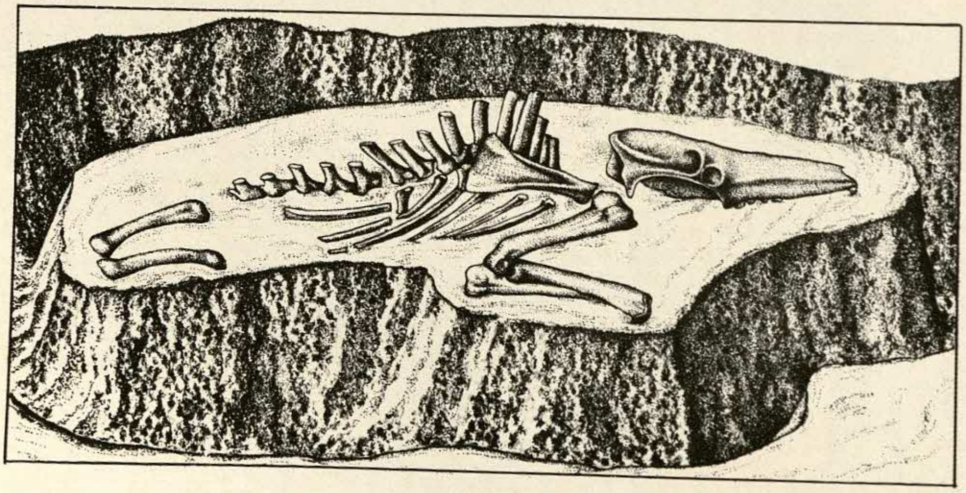
2a



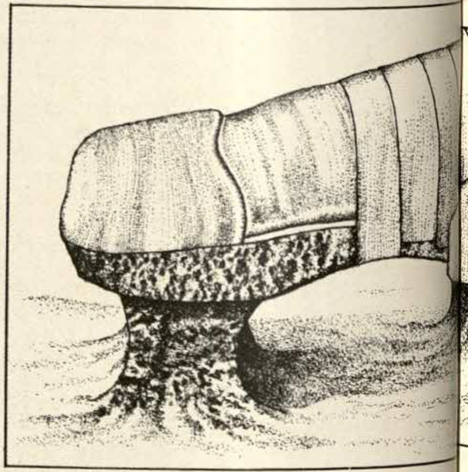
2c



2b



2d



THE VERTEBRATE BODY

The vertebrates include a variety of animals that superficially seem to be very different. Some swim, others walk or run, and still others fly. They are variously covered with scales, feathers, fur, or merely naked skin.

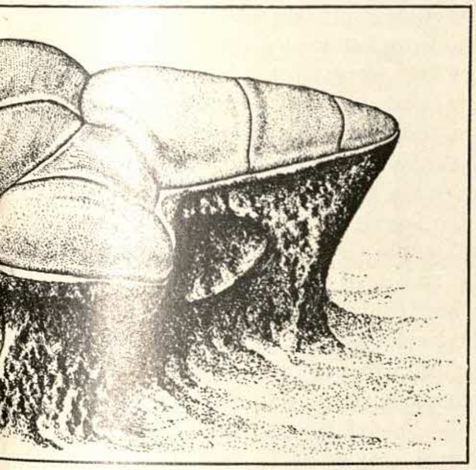
Despite their diversity, their bodies have certain anatomical similarities. Except for the lampreys, adult vertebrates have an internal skeleton consisting either of cartilage only or of bone with some cartilage. The main supporting structure is a backbone consisting of a row of vertebrae that lie near the dorsal surface and extend nearly the length of the body. There usually are two pairs of fins in fish and two pairs of limbs in the other vertebrates. A skull at the anterior end protects the brain, and a set of ribs protect the heart and other internal organs.

The spinal cord is a dorsal nerve cord that extends posteriorly from the brain and is protected by the vertebral or spinal column. The spinal cord gives off pairs of nerves at repeated intervals. They run to the skin, muscles, and internal organs. The brain, an enlargement of the spinal cord, lies in the head where many of the sense organs are located, especially those of sight, hearing, and smell. The brain, too, gives off a series of nerves. The concentration of sense organs in the anterior part of the animal is advantageous for rapidly moving animals that hunt for prey or must escape from predators.

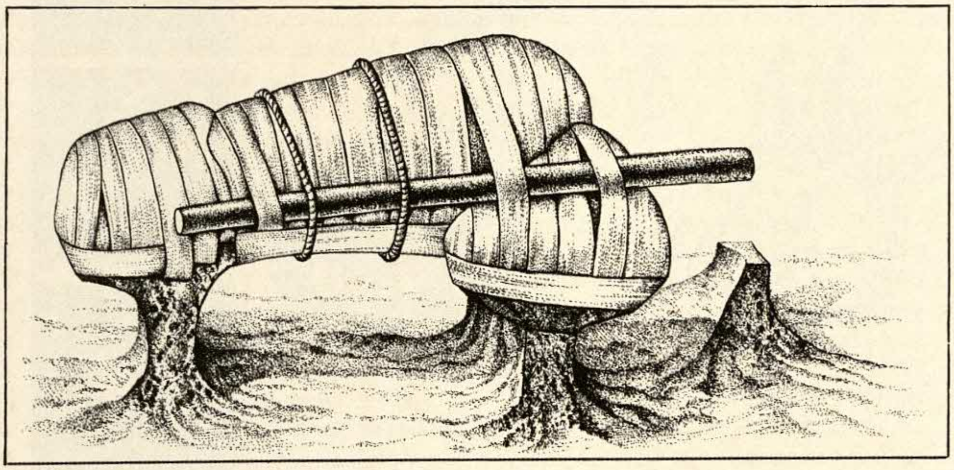
---

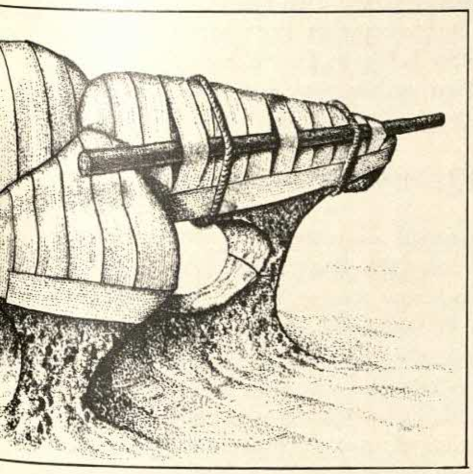
in separate blocks (as shown in Illustration 2c). Strips of cloth are wound around the plaster blocks. Illustration 2d shows how wooden or metal rods may be included to keep the blocks from breaking. The fossil is isolated by digging underneath it, and the pieces are removed one at a time (Illustrations 2e and 2f). All work is performed with extreme care, for fossils are fragile.

When the fossil arrives in the laboratory, the protective coverings are removed. Then fine tools are used to separate the remaining rock from the fossil. The bones are then assembled as they were in life. If the bones are fragmented, reconstruction is arduous.

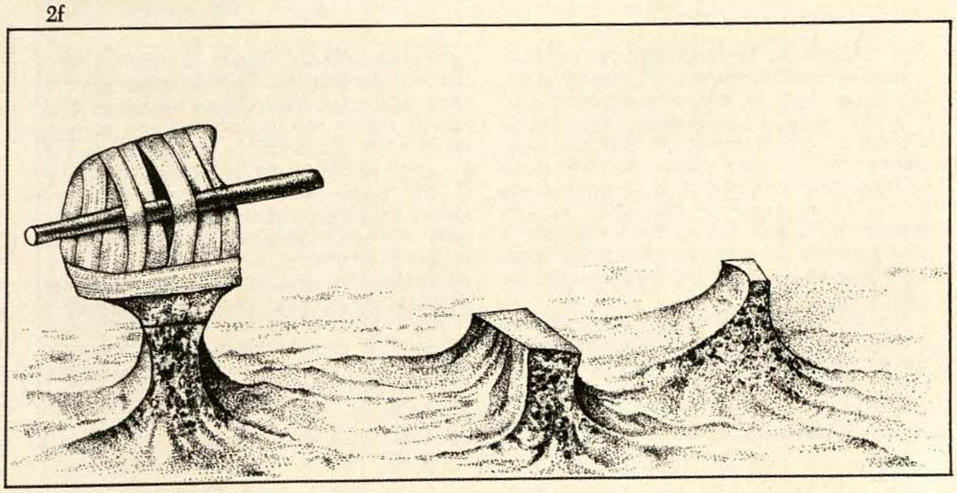


2e





2f



The heart and the main blood vessels lie in the ventral part of the body.

Most aquatic vertebrates obtain oxygen from water passing through their gills. Air-breathing aquatic animals and terrestrial vertebrates have lungs.

ANCESTRY OF THE VERTEBRATES

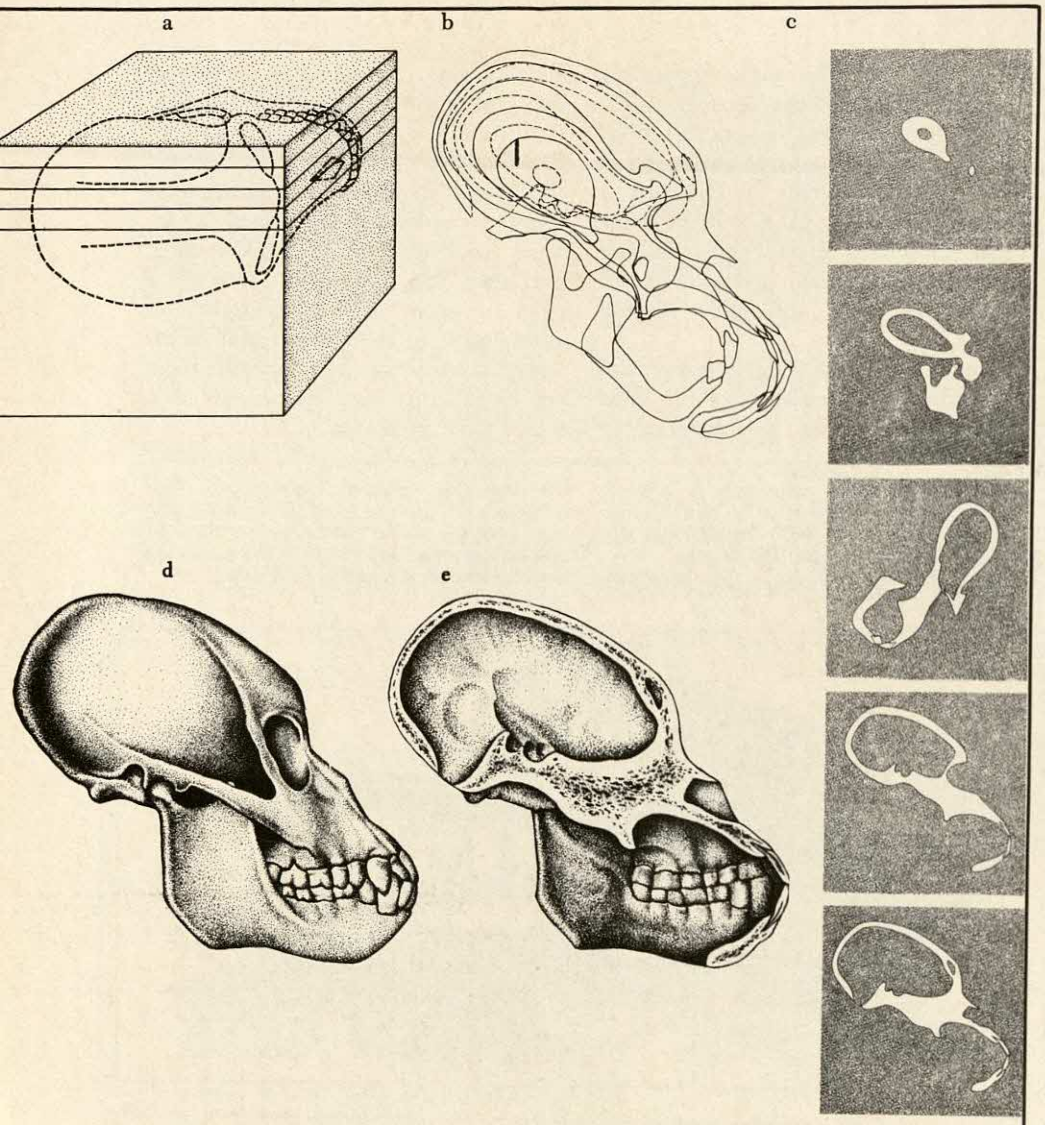
The ancestry of the vertebrates is almost as much a mystery as is the time of their origin. Where no fossil evidence exists, it is often possible to obtain clues by looking for anatomical similarities among living organisms; those that resemble each other greatly usually are closely related. This line of study has revealed little about vertebrate ancestry, for few of the invertebrates have body plans similar to that of adult vertebrates.

An interesting clue came to light when it was discovered that the larvae of the echinoderms (starfishes and sea urchins) are nearly identical to those of acorn worms and lancelets, simple invertebrates that share enough characteristics with the vertebrates to be classified with them in the Phylum Chordata. Not only are the larvae of the echinoderms and these simple chordates similar, but the early stages of their embryology are very much alike, and they differ from the early development of the embryos of the other major groups of invertebrates. The biochemistry of the echinoderms also resembles that of the vertebrates and differs from that of other invertebrates in several respects. These facts have led to the conclusion that some primitive echinoderm living in the Ordovician period or even earlier may have been the ancestor of all vertebrates.

VERTEBRATE FOSSILS

The fossils of vertebrates often consist only of their bones, for these endure much longer than soft tissues. The bones may be infiltrated with minerals or even completely replaced by them in time, but evidence of the shape and size is preserved. From this information the general appearance of the animals in life can be inferred with reasonable accuracy. Occasionally the hide and fur are preserved as well, and some animals have been found frozen intact in ice.

3



THE TECHNIQUE OF PARALLEL SECTIONS— A very important technique in the study of the vertebrate fossils is that of parallel sections. It is often difficult to reconstruct the form of a complex bone structure, like that of a skull, merely from the fossil remains that have come to light. Scientists, therefore, have recourse to the device shown in Illustration 3a. The structure is encased in a hard material; it thus becomes possible to handle the fossil with ease and also to carry out mechanical work on it.

The block thus obtained is then ground on one side (either on the front or on other sides, as preferred) so as barely to expose the fossil, and the section obtained is photographed. The block is ground down further until a new deeper section is obtained, and this is photographed. Further grindings and photographs are made. These photographs of parallel planes can be enlarged and aligned, as shown in Illustration 3b. Reconstruction of the fossil is carried out by placing the profile of the various sections on glass slabs arranged parallel to and at such a distance from each other as to preserve the same relations as those existing in the object under study (Illustration 3c). This method causes the destruction of the fossil, but the advantage it offers amply justifies this destruction when the fossil is a fairly common one. It is possible to draw not only the outer form of the skull but also that of its sections (Illustrations 3d and 3e).

CHEMICAL FOSSIL SUBSTANCES

Until a century ago, fossils arrived in the laboratory still embedded in their rock matrix and then were carefully freed from it in preparation for observation and study. Paleontological studies continued in this laborious way until two new research methods were developed. First, paleontologists began sectioning and analyzing their specimens, working on the principle that fossilization is a chemical and physical process in which other matter takes the place of the original animal and vegetable matter and that animal and vegetable parts composed of different substances turn into fossils with correspondingly different compositions. A second big step forward was the ever-widening search for fossils of microscopic dimensions, which abound in certain soils. Today, such paleontological prospecting is widely employed in the exact dating of strata and levels in soils—information of great interest, for example, to those prospecting for oil.

Oil is a mixture of liquid, gaseous, and solid hydrocarbons found in sedimentary rock deposits. The mother substance of oil consists of plant and animal remains in near-shore marine sapropelic sediments. Part of the remains originated in the sea and part were carried to the sea by rivers. The marine sediment eventually turned into rock. In time, orogeny buried the deposits; and the heat and pressure caused by the weight of overlying rock, together with decomposition of the organic life, formed oil.

CHEMICAL FOSSIL SUBSTANCES

The stone in which a fossil is embedded may be impregnated with traces of organic substances produced by the decomposition of the fossil. In some cases, this decomposition took place along a whole stratum containing an enormous number of fossils, so that the entire rock level was ultimately impregnated with such traces. This occurs in the so-called ichthyolitic shales, which are impregnated with bitumen of organic origin. In these cases, study of the organic substances is only of comparative importance. Once the fossils have been identified, it is possible, by analogy with present life-forms, to determine the composition of the substances from which the fossil matter was formed.

A far more complex problem exists, however, in the case of organic substances of animal or vegetable origin sometimes found in rocks containing no other traces of fossils. If, for example, old sediments, dating back from 1 to more than 3 billion years, are examined, the researcher will discover that they are full of organic substances of biological origin. In such a biological journey back in time, the first fossils whose original form has been identified were minute, multicellular algae. The evolution of the even more primitive unicellular algae must have occurred early in the Earth's development. Unicellular algae may never be found in the form of fossils with dimensions and shapes recognizable under the microscope, but such algae may also have left traces in the form of organic substances into which they decomposed.

Many paleontologists are now devoting their time to an exhaustive search for and interpretation of traces of the oldest forms of life. This new branch of paleontology presents two problems: that of extracting the remains of the organic substances of biological origin from the rocks in which they are contained (a purely technological problem), and that of interpreting the role that these substances must have played in the primitive evolution of life.

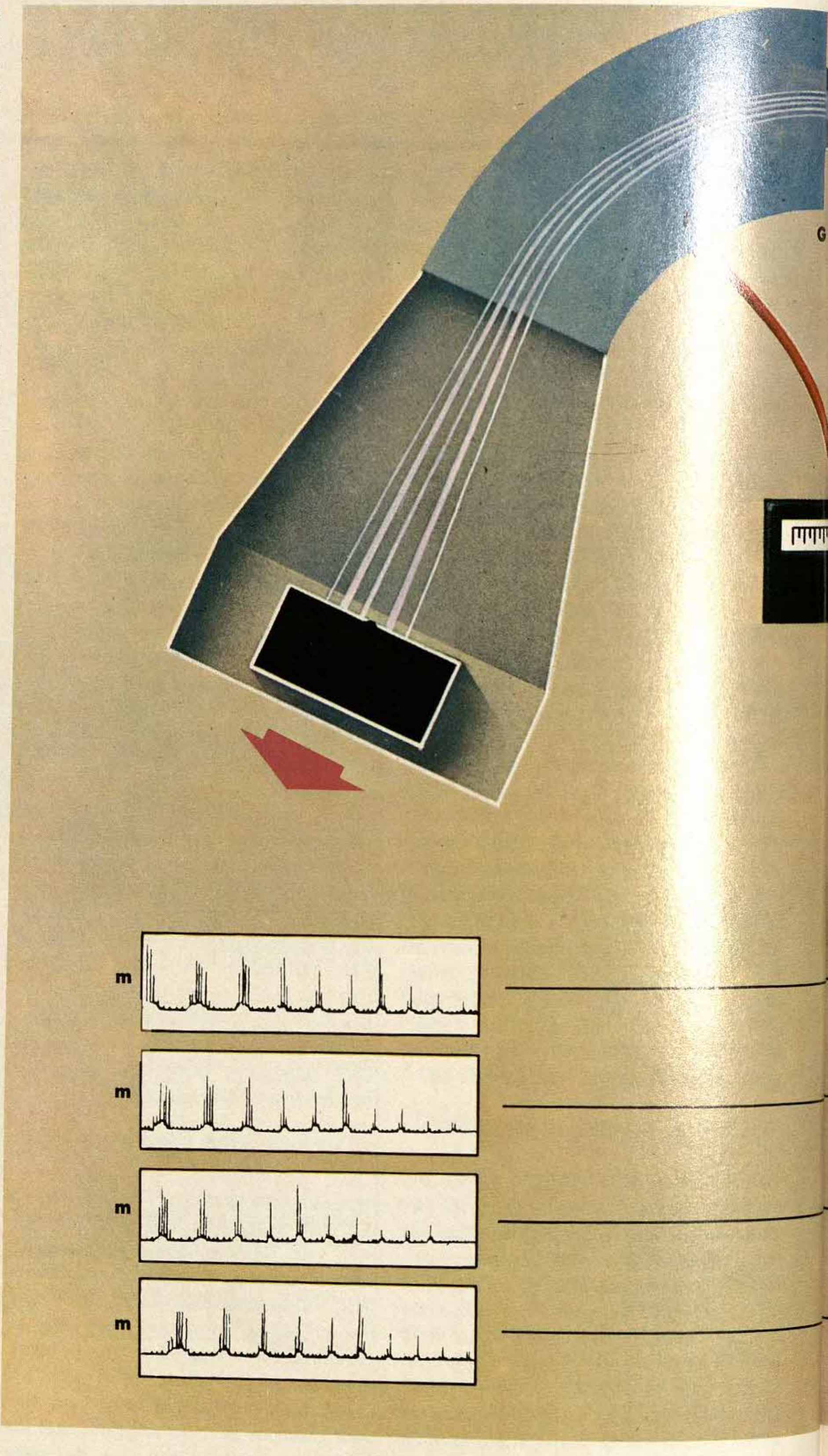
PRINCIPLE AND METHODS

Research into chemical fossil substances is based on the fact that living beings—even such primitive forms as unicellular algae—synthesize organic substances that, on decomposition after death, give rise to simple substances that may be preserved for a long time. The basic assumption is that these substances can be of biological origin only, and that their presence in rocks indicates that life existed on Earth at the time the rocks were formed.

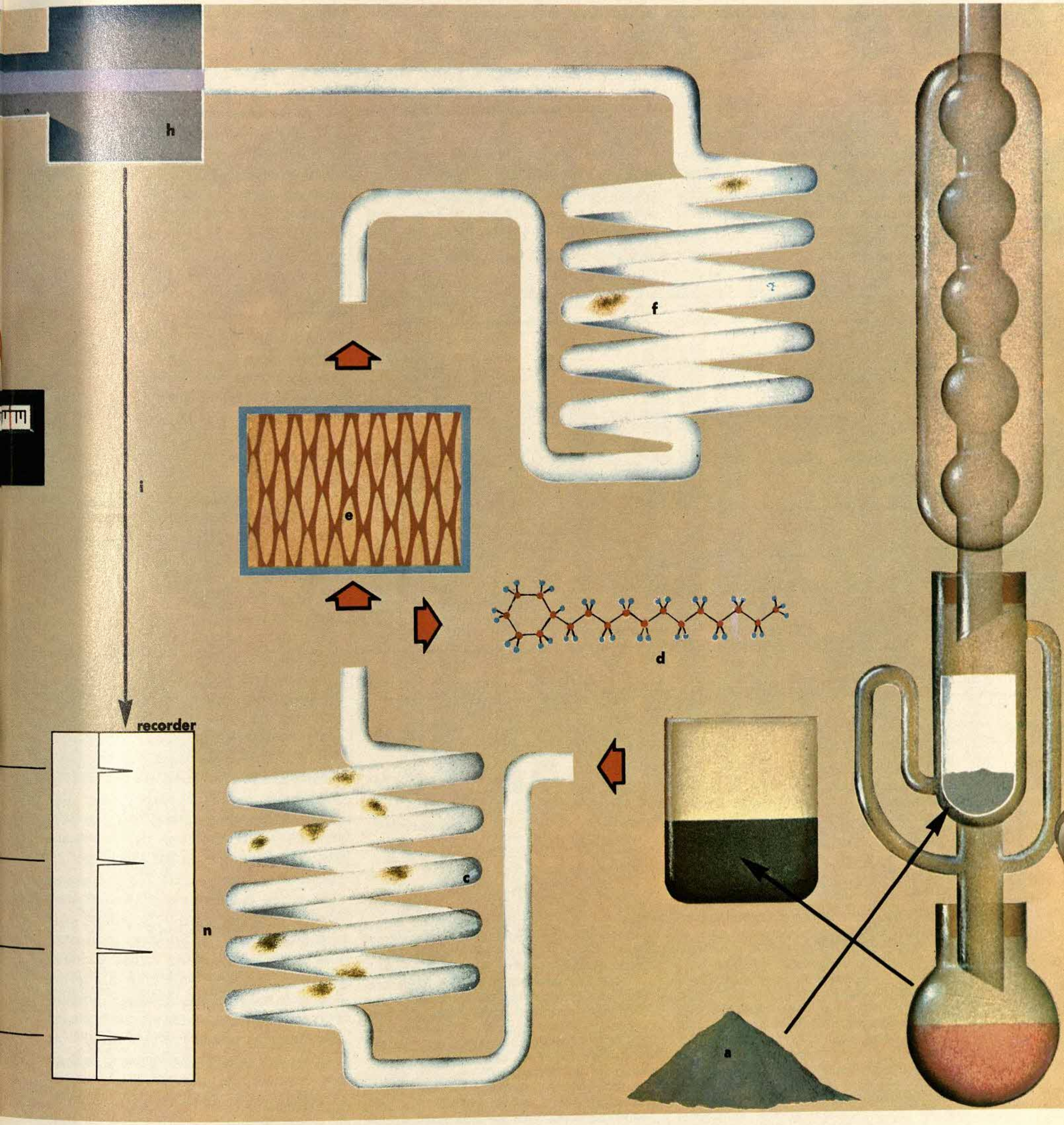
There remains, of course, the possibility (also common to other geochemical researches) that these substances were introduced into the rock after its formation, or even that their presence may result from careless handling in the laboratory. These doubts can be eliminated, however, by taking the necessary precautions and performing appropriate tests. So far, about fifteen classes of organic compounds that can be considered true chemical fossils are known. Of these, some can be preserved only for a short time while others may last more than a billion years. Research is carried out in two stages: first, the extraction of the organic substances from the rock sample, and second, the analysis of the extracted substances. Modern resources and instruments are utilized by researchers to make it possible to find even the most minute traces of these organic substances.

To extract the organic substances from rock, consideration must be given to the type of rock to be analyzed. Usually the rocks are shales—foliated rocks that cleave easily and are porous. Such rocks contain foreign substances, which may have infiltrated during the formation of the rock. To extract these substances, the rock is pulverized; the particles are then placed in an apparatus that extracts the organic substances by means of solvents. The inorganic matrix is completely resistant to solvents. If it is believed that the organic content will be small, the rock is first destroyed with hydrochloric and hydrofluoric acids, which dissolve the chief mineral components. However, the hydrocarbons, which are the main ingredient of the organic substances being sought, are not affected by this process. Researchers thus obtain a mixture of organic substances, often in microgram quantities, which have to be separated.

A gas chromatographic technique is used to separate organic matter. The substances are extracted through a column filled with aluminum oxide and are carried by a gas such as helium. The speed with which the substances cross the column depends on their composition and varies from one molecule to the next. The substances leave the chromatographic column in succession and are collected separately. A second chromatographic separation may be necessary, using both gas and liquid as carriers for the substances. At this point, the chromatograph furnishes a series of substances that are analyzed individually. Before detailed analysis takes place, a special separation is made in which molecules made up of simple aliphatic chains are isolated from those whose structure contains branched chains or rings. The separation process employs certain clays that swell and allow the molecules of the simple hydrocarbons to penetrate while shutting out the more complex molecules. Once the fractions have been separated, they are submitted to mass spectroscopy and infrared absorption. Through these forms of analysis, researchers are able to establish the nature of the organic molecules of the rock. At this point the task of interpretation begins.



MOLECULES THROUGH A SIEVE—This illustration shows the steps by which the organic material content of a rock is analyzed. Pulverized rock **a** undergoes normal extraction by means of solvents **b.** The total lipid extract is introduced into a gas chromatograph **c;** the alkane fraction **d** is extracted, and the remainder is discarded or kept for further analysis. The fraction is put through a molecular sieve **e,** consisting of a substance such as montmorillonitic clay, which has the property of swelling when certain molecules enter its crystalline structure. Only the simple alkane molecules without branches or closed rings pass into this sieve, and are thus separated from more complex molecules. The latter are introduced into a second gas chromatograph **f,** which separates them. The exit from this chromatograph leads directly to the entrance of a mass spectrograph **G.** At **h** the molecules are bombarded with an electron beam. Then, having been ionized or electrically charged, they are accelerated. Variations in the intensity of the ion current **i** are registered on a recorder, which produces a chromatogram of what is being analyzed. The magnetic separator **l** separates the different fragments before the slit of the receiver of the mass spectrograph; the receiver then produces a current in proportion to the intensity of each mass received. In this way researchers obtain a recording, parallel to that of the chromatograph, and containing the mass spectra of the substances analyzed. The diagrams **n** and **m** are respectively the chromatogram and the mass spectra of the peaks of the chromatogram, which correspond exactly. The composition of all the molecules contained in the rock is then determined by infrared spectroscopy.


h
f
i
e
d
recorder
c
n
a

PALEOBIOCHEMISTRY | tracing the beginnings of life

Since the dawn of human intelligence man has looked beyond the problems of survival to ponder the mysteries of the origin of life. What is life, and when and how did it begin? Who, or what power, conceived and brought into being man and the objects around him—the land and water animals and plants, the cycles of the seasons, the stars in the heavens?

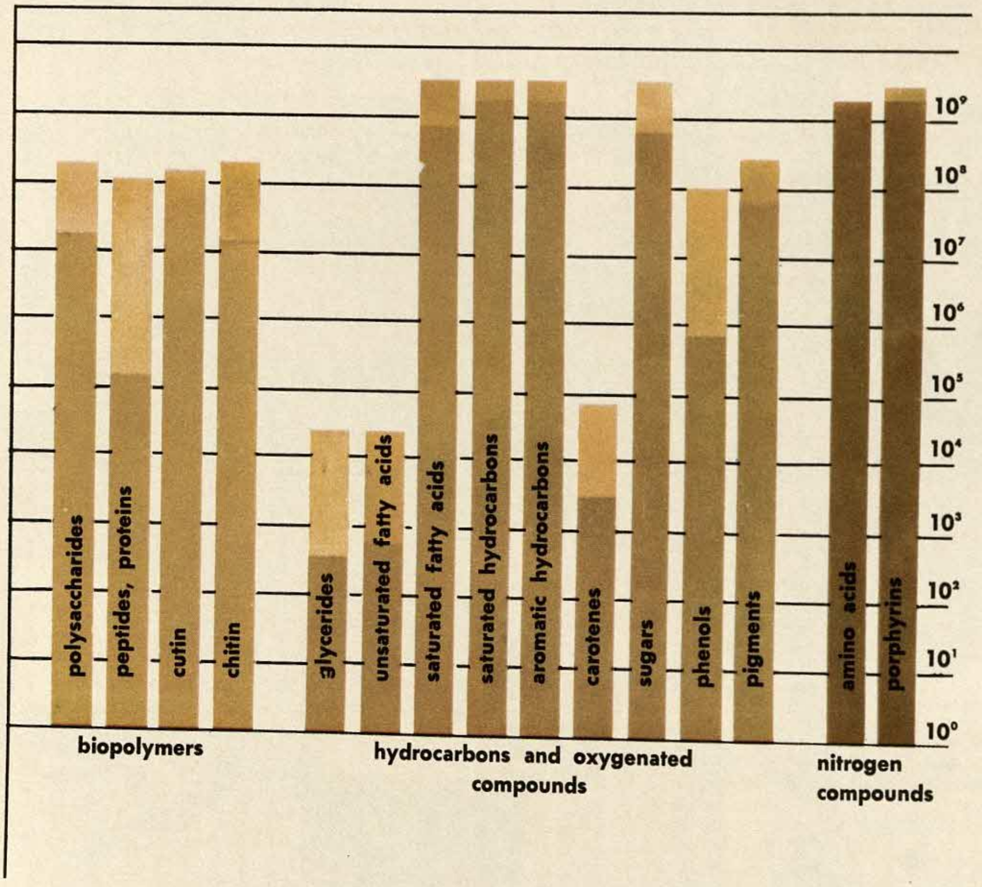
The answers to some of these questions remain as obscure as they were in prehistoric times. However, in recent decades man has answered at least some of the questions concerning the evolution of life. For example, the analysis of chemical fossil substances, which has disclosed traces of biological matter dating back some 3 billion years, has thrown new light on the early processes of evolution.

1

Geological studies have placed the age of the Earth at 5 or, at most, 6 billion years. Until the study of chemical fossil substances began, it was believed that the first forms of life on Earth—bacteria and algae—began to emerge about 2.7 billion years ago. However, the analysis of chemical fossil substances makes it possible to trace organic remains back to even earlier times. These indicators serve as evidence that biological evolution began very early in the Earth's history, and that it was probably preceded by a purely chemical evolution of the substances present on the surface of the globe.

Very little is known about the history of this chemical evolution. Since the study of chemical fossil substances is only a recent one, much remains to be discovered about the relations between these substances and the ancient types of living forms from which they may have derived. The entire history of the so-called chemical evolution of life still awaits factual reconstruction, and for the moment science can only proceed by educated speculation. However, inasmuch as biological evolution appeared so early on Earth, many scientists are convinced that chemical evolution must have begun as soon as the planet had cooled sufficiently to permit the molecular stability of substances. In brief, it is theorized that the history of life on Earth had its chemical prelude as soon as the Earth had cooled.

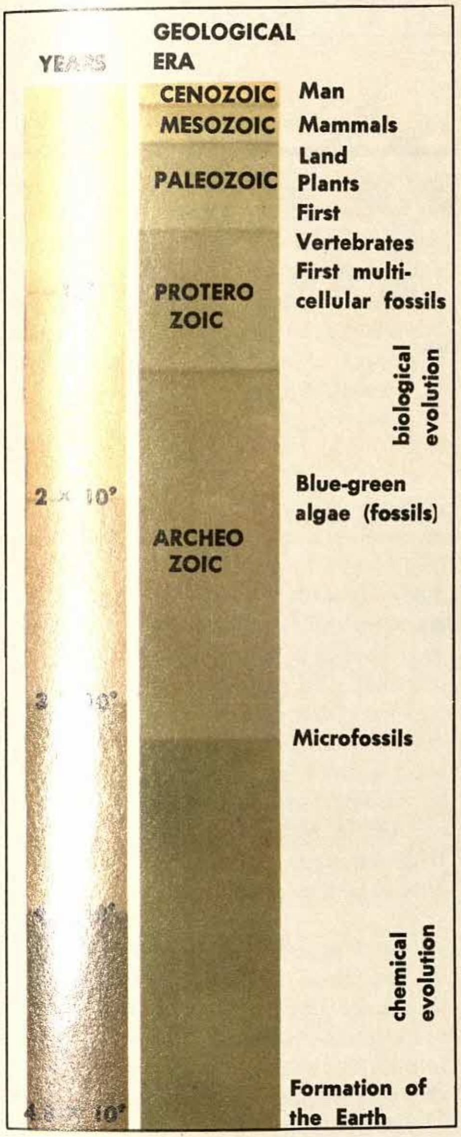
For the present, though, the study of evolution is still limited to the so-called biological period. In practice, studies of the early stages of this period are concentrated on research into certain organic substances and their correlation with life forms from which they may have originated, and on the process of degradation which occurred after the death of the living matter. This practical research is accompanied by theoretical study of the processes by which the organic substances formed. No specimens exist of the life-forms of the far-distant past, so it is not possible to know with certainty what physiological processes took place in this living matter. Science can only study the analogous life-forms that exist today. Although there must be a great difference between these forms and those of the beginnings of life on Earth, some biological processes, such as the formation of chlorophyll, have not changed despite the passage of billions of years and the drastic changes that have taken place in life-forms. The continuity of such biological processes helps to link present and primeval forms.



PRESENT-DAY KNOWLEDGE IN PALEOBIOCHEMISTRY—This graph shows the state of present-day knowledge of paleobiochemistry.

The vertical axis indicates the time on a logarithmic scale, while the columns indicate the age of the various compounds identified. The amino acids have been traced back as far as 2 billion years, while other compounds have been traced back only about 1,000 years. There are two reasons for these differences in the limits of identification: first, thorough research into all the possible types of the oldest sediments still has to be carried out; second, decomposition of the substances takes place in such a way that it is difficult to reconstruct them by working back from molecular fragments. Because research is on the increase and more and more samples are now being analyzed, both these difficulties should soon be overcome. Furthermore, great progress is being made in the analysis of the evolutionary history of substances and of their processes of decomposition and degeneration. The lighter-colored parts of some of the columns indicate time spans for which identification of a substance is not certain. This lack of certainty is due to the fact that the compounds into which that substance decomposes are not known with any accuracy, or else that, once the compound has been found, uncertainty exists as to whether the compound originated from just one substance. In the future, when more is known about the process of decomposition, it will be possible to identify these substances with greater certainty, thus spurring research.

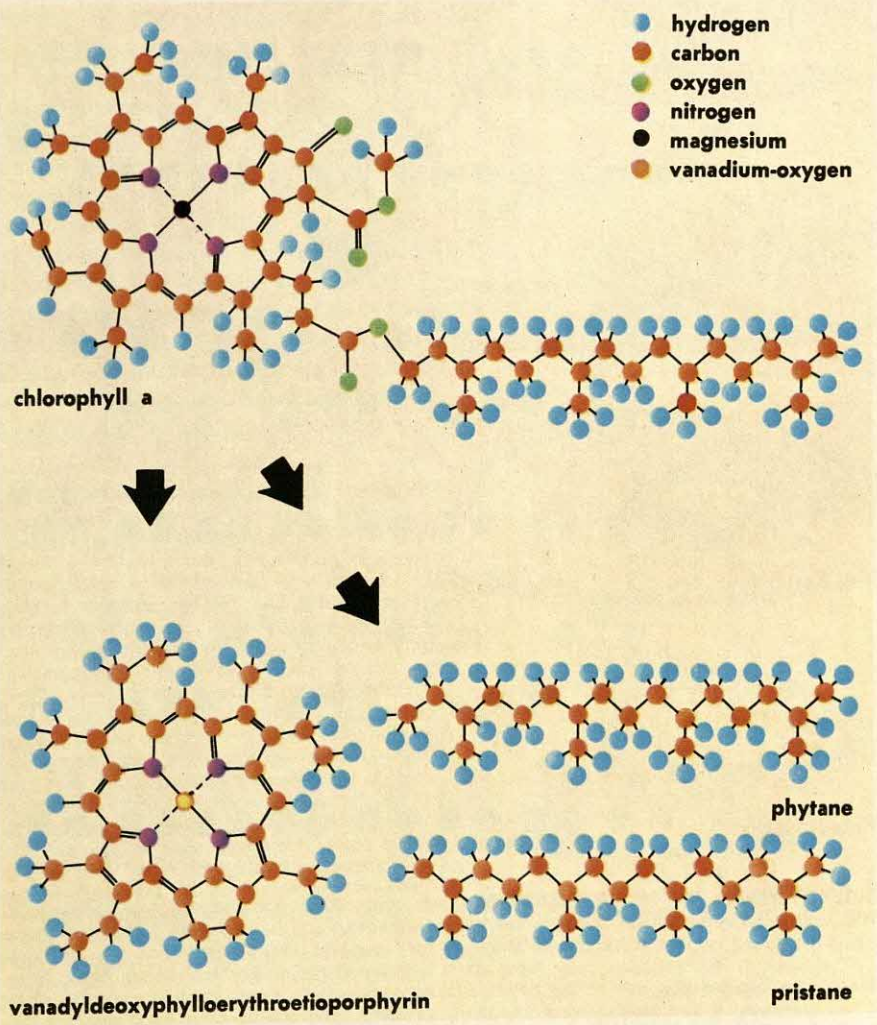
2



THE CHEMICAL AND BIOLOGICAL EVOLUTION OF THE EARTH—As noted previously, recent studies have led to the conviction that chemical and biological evolution began as soon as the Earth had cooled.

The scale used in this diagram is linear. The most recent events, such as the appearance of mammals, are included in a small space at the top of the diagram. Their appearance is, in fact, very recent—the last stage in the evolution of living beings. The first multicellular fossils have been traced back a billion years, although it is probable they were present on Earth in more remote times. The oldest algae made their appearance 2 to 3 billion years ago, while the first microfossils probably go back 3.3 billion years. It is not known if other, even more primitive forms of life existed before this. If they did exist, they must have been derived from forms that are still unknown—forms that served as the link in the transition between the organic and biological worlds. Before the appearance of the first microscopic organisms, a chemical evolution undoubtedly prepared the way for life. For this reason, the time sequence shown is divided into two major periods—that of biological evolution and that of chemical evolution. Life began to emerge on Earth as soon as the planet cooled, with the chemical evolution quickly paving the way for the biological evolution.

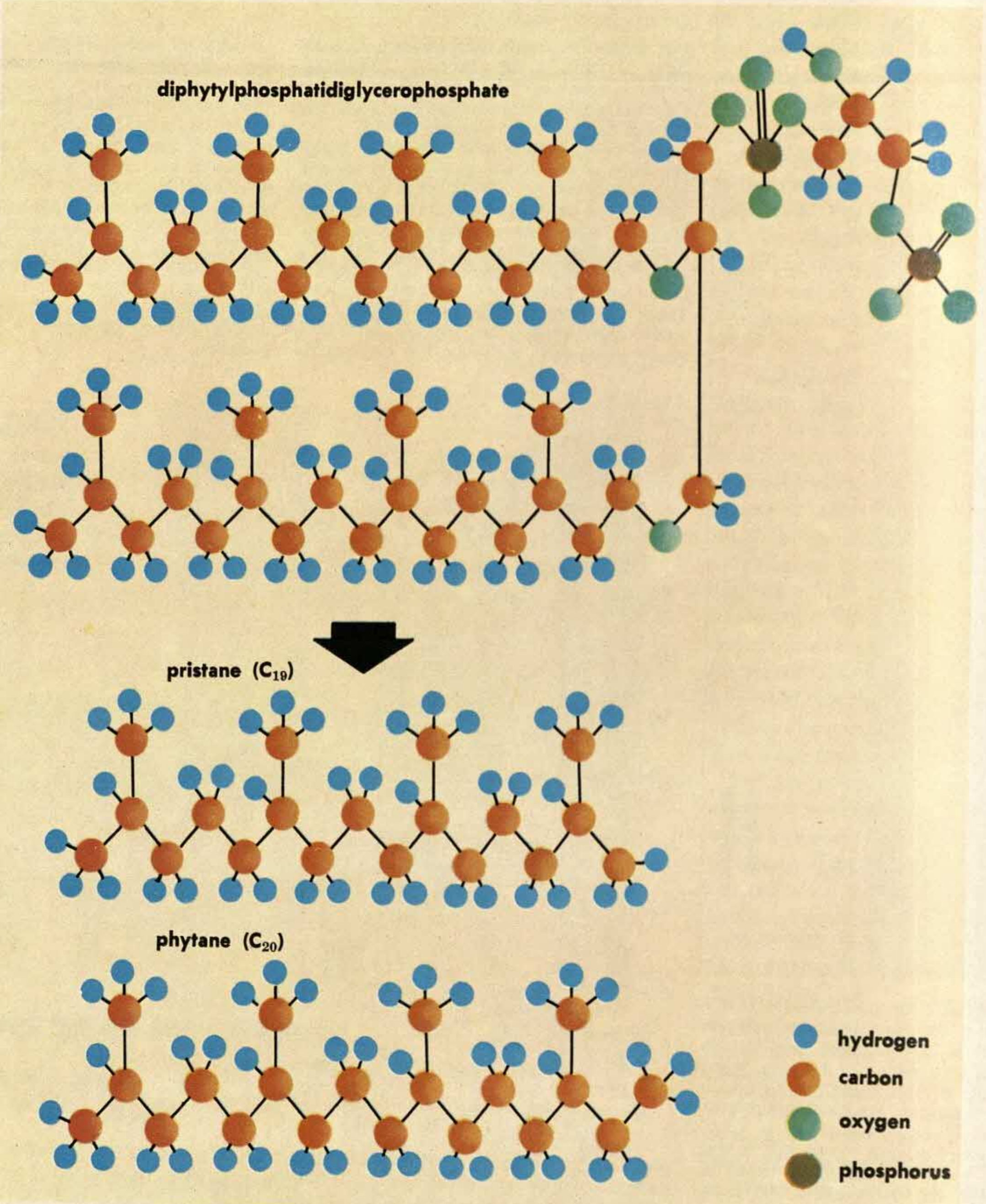
3



THE DEGRADATION OF CHLOROPHYLL A—The structure at the top shows the molecule of chlorophyll a, the element essential to plant life. It is so common in the plant world that it is found in large quantities—although in degraded form—in chemical fossil substances.

The structure of original chlorophyll is that of a group of 4 pyrrole rings, in the center of which is a magnesium atom, and a side chain with 20 carbon atoms. The degradation of chlorophyll takes place in two ways. First, the molecule breaks at the point where the side chain is attached to the rings of the main group. This causes the isolation of the side chain with 20 carbon atoms, which is known as phytane. Second, in the breakaway, the chain may be left with only 19 carbon atoms; in this case, pristane is formed. The main group, on the other hand, keeps its form despite degradation, but the central magnesium atom is replaced by one of vanadium and one of oxygen. This compound, vanadyldeoxyphylloerythroetioporphyrin, is one that is frequently found in crude oil. Its origin, therefore, can only be due to plant degradation.

4



ANOTHER ORIGIN FOR PHYTANE AND PRISTANE—Phytane and pristane, the two isolated chains produced by the molecule of chlorophyll a when it decomposes, may have another origin besides that due to the degradation of chlorophyll. Two such chains are also found in a phosphatide present in some present-day primitive organisms—bacteria that live in salt water. Shown here are the isoprenoid chains of both substances linked to form diphytylphosphatidiglycerophosphate. Degradation of the molecule of this substance may lead to the formation of the two free isoprenoid chains in the chemical fossil. However, scientists must proceed carefully when drawing conclusions about the origin of a fossil substance. For example, the simultaneous presence of the porphyrin ring and of the isoprenoid chains may confirm the presence of chlorophyll in the biological environment from which these substances emerged, whereas the presence of isoprenoid chains alone signifies the presence of the halophylic bacterium. In general, therefore, the study of fossil substances must go hand in hand with careful evaluation of the conditions in which these substances originated, from the history of the formation of the rock to that of its ensuing evolution.

LOCOMOTION IN WATER | the evolution of aquatic movement

Since the first unicellular beings came into existence, locomotion has always been an important part of animal life. Movement enables an organism to search for food and is thus a necessity for nearly all animals. In the course of millions of years of evolution, rapidly moving aquatic animals developed streamlined shapes that enable them to maneuver quickly and efficiently through water.

HOW A FISH SWIMS

Any locomotion of animals—whether swimming, flying, or walking—presents certain problems. Unlike birds, which are heavier than the air through which they fly, the bodies of most fish are equal in density to the water in which they live. As a result, fish have little difficulty in staying submerged. A fish, however, swims in a medium that is practically incompressible; it must push water aside if it is to move. The fish's method of swimming takes advantage of the incompressibility of water—it pushes itself forward by forcing water to flow behind it.

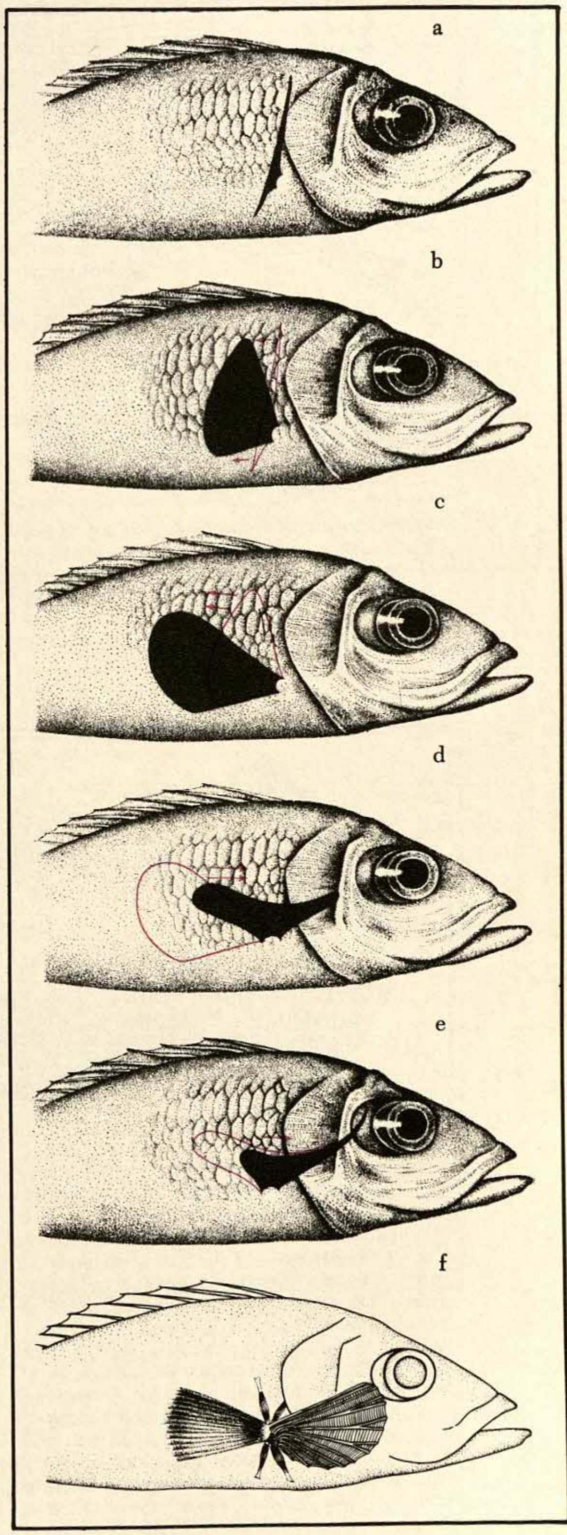
A fish propels itself forward not by moving directly forward itself, but by twisting its body from side to side in graceful curves. When the head moves to the right, water along the right side of the animal is forced backward along its body; when the head moves to the left, water on the left side is forced backward. This backward flow of water causes the fish to move forward. When viewed from above, the fish appears to move along a wavy path.

The tail fin, as an extension of the body, is involved in the twisting motions that propel the body forward. The other fins, which do not contribute much to forward propulsion, are used in balancing and steering. The pectoral fins (the paired fins immediately behind the gills) and the pelvic fins (the paired fins farther back on the body) serve to turn the fish in a horizontal plane. Upward and downward movements are controlled in part by the dorsal and anal fins, along with the tail fin. The size, shape, and position of fins vary with the species and the habitat in which they live.

Some fish have a swim bladder—a sack that absorbs gases from the fish's blood. The volume of gases in the swim bladder is adjusted so as to give the buoyancy necessary to maintain a particular depth. Fish without swim bladders must rely on swimming movements to keep from sinking.

Cyclostomes, among the lower classes of fish, are inefficient swimmers that propel themselves by body undulations, making little forward progress. The most speed probably is attained by members of the group of mackerel-like fishes to which the tuna and marlin belong. Cartilaginous fishes, such as sharks, swim well but not especially fast. Besides swimming, methods of locomotion include jumping and gliding. The salmon leaps as high as nine feet into the air, and the devilfish can leap up for a few feet. Flying fishes have enlarged pectoral fins that enable them to break the surface and, in some species, to glide for long distances. Many game fish break the surface trying to free themselves from a hook.

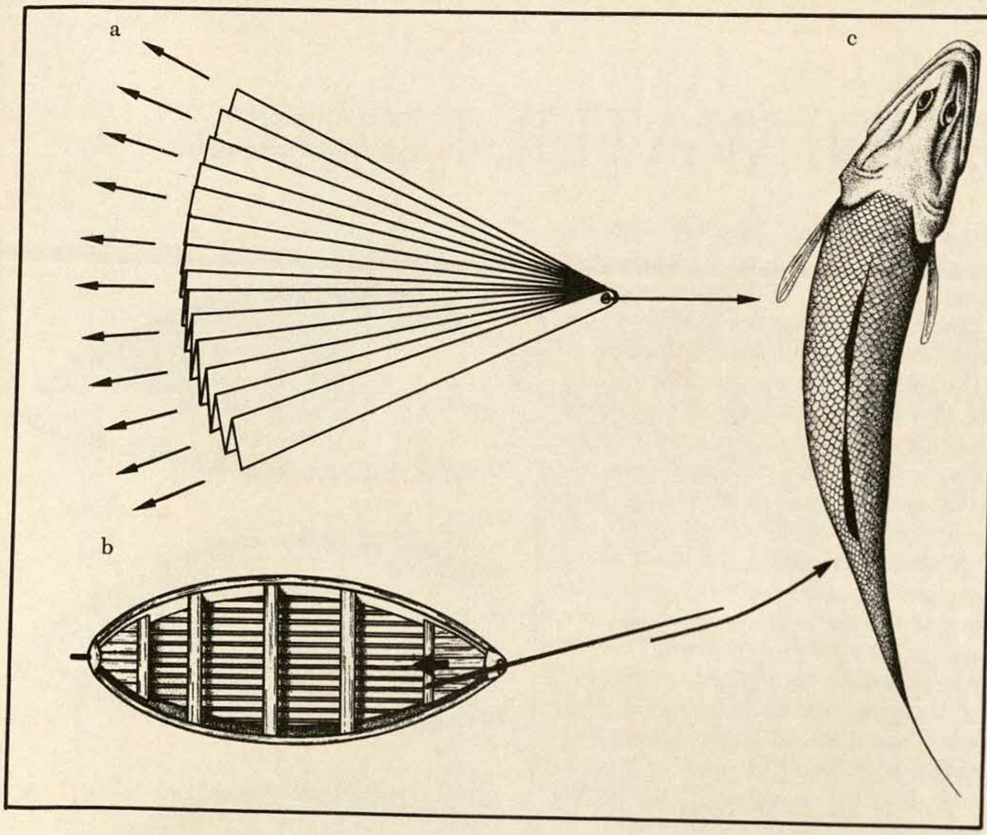
1



THE INEFFICIENCY OF FINS—Many fish have large fins, but very few use these fins in a "rowing" manner as their chief means of propulsion. First of all, the rowing method of propulsion is complicated and requires a complex muscular system; and second, most fish possess a much more effective system. From top to bottom, the illustration shows the movement of the pectoral fin when the fish is moving in a forward direction. In Illustrations 1a, 1b, and 1c, the fin is moving backward and driving the water in this direction, and the fish moves forward. As the fin moves backward it is held vertically, perpendicular to the direction in which the animal is moving; when the fin moves forward, however, it cannot hold this vertical plane because it would tend to drive the fish backward. Illustrations 1d and 1e show that, as the fin moves forward, it is held horizontally and is oriented parallel to the direction of the fish's movement. The fin in Illustration 1c is pointing upward at an angle of 30° as it shifts from a backward to a forward stroke and begins to move into a vertical position again. Then it is thrust vigorously backward and the cycle begins again.

Illustration 1f shows the muscles used in moving the fin. Because they are slender and not very powerful, they are unable to exert great effort.

2



SWIMMING MOVEMENTS OF A FISH—The movement of a fish through water shares some similarities with the use of a fan in air and the sculling of a small boat in water.

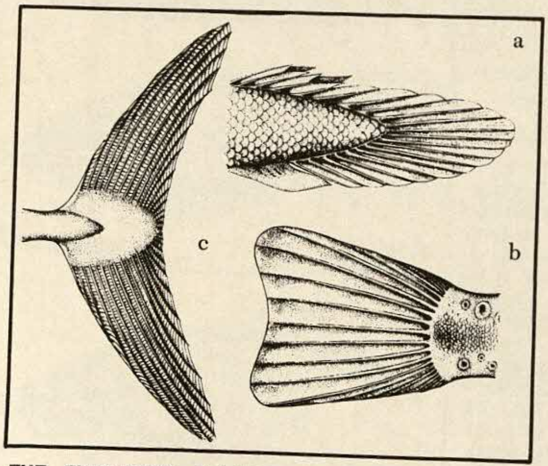
When a fan is moved through an arc of about 90° (Illustration 2a), it drives the air backward in the direction shown by the single arrow. This causes air to move forward in the direction indicated by the other arrows.

The same principle is sometimes used when boats are forced to move in narrow waters and cannot be propelled by lateral oars. A single oar, called a scull, is located in the stern of the boat. The scull is worked like a rudder to right and left with respect to the longitudinal axis of the boat. This produces a backward movement of the water; water moving in behind the boat drives it forward.

This same principle of the fan and the scull is used by a swimming fish. The fish utilizes the whole of its body, including its tail, to drive water backward, thus causing a forward reaction. The alternating twisting movement of the body of the fish works the tail and the posterior end of its body like a scull. The body bends, because the muscles on one side of the body contract while those on the other side relax. Alternate contracting and relaxing of muscles on each side causes the twisting motion.

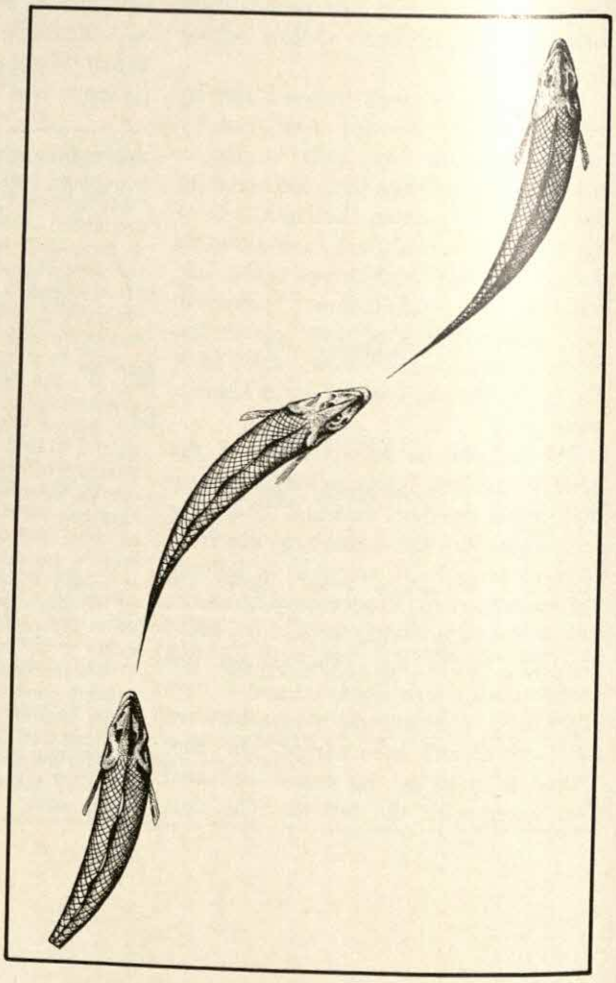
THE PATH OF A SWIMMING FISH—A fish moving forward twists its body alternately right and left. As the movement of the fish is continuous and almost uniform, the curvature of its body follows a path shaped like a sine wave. Although the fish moves forward, the wavy path remains stationary with respect to the water.

4

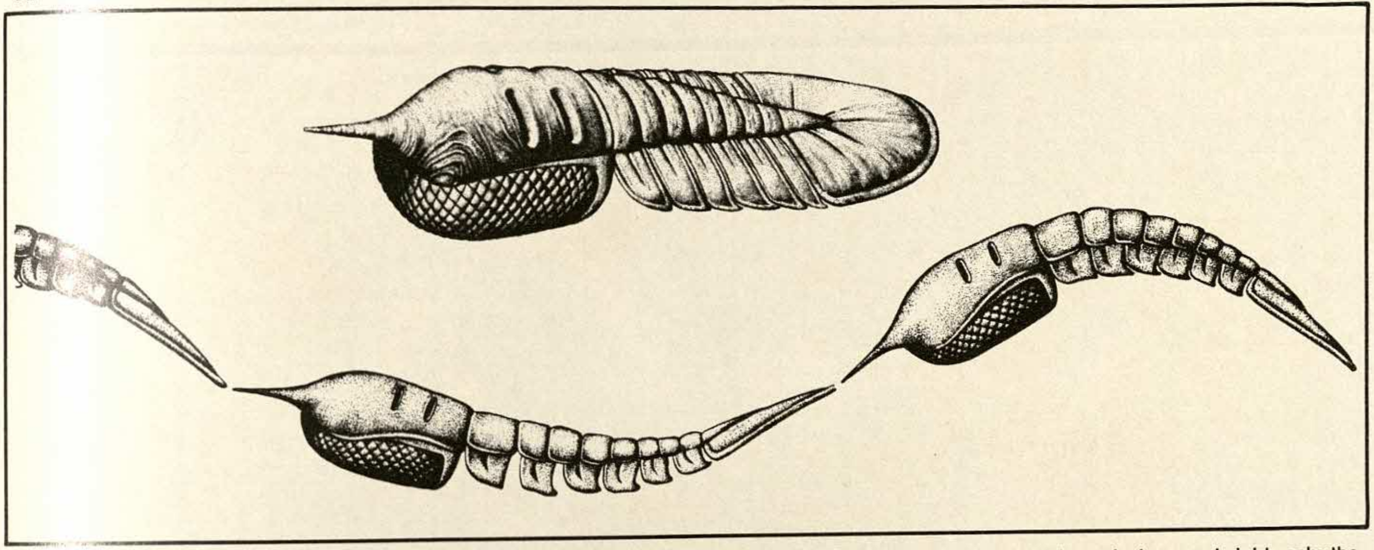


THE EVOLUTION OF THE TAIL TOWARD HYDRODYNAMIC PERFECTION—The tail of a fish has several functions: it acts as a rudder; it is involved in upward swimming movements; and it reduces turbulence caused by movement of the fish. Many millions of years of evolution have perfected tails that are considered to be hydrodynamically ideal. In the earliest fish the spine extended the length of the tail. In somewhat more highly evolved fish (Illustrations 4a and 4b), the spine stopped short of the tail, which was supported only by fine bones. The tuna has a tail with two blades, one dorsal and one ventral (Illustration 4c). The flow of water around such a shape involves minimum dispersion; thus, a thin tail offering little resistance is capable of producing a considerable forward thrust.

3



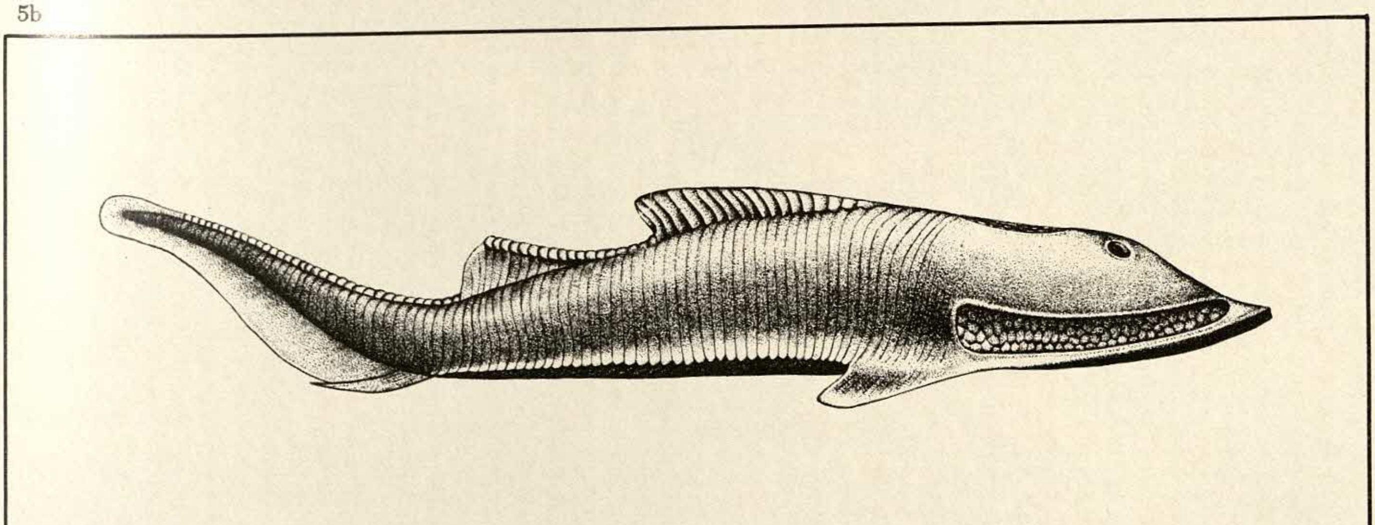
5a



TRILOBITES AND CYCLOSTOMES—The trilobite (illustration 5a) was the first aquatic animal to utilize the principle of the scull as a system of locomotion. The articulation of its segments allowed the body to arch upward and downward—virtually the same movement as that made by modern fish, but in a vertical rather than a horizontal plane. The trilobite, unable to reach any great speed by this method, also used its weak legs for locomotion on the sea or river bottom.

The cyclostomes were primitive eellike fish. *Aceraspis robusta* (Illustration 5b) swam in a manner similar to that of the trilobites (although it was not related to them). The head of this primitive fish-shaped vertebrate was flat in the horizontal plane and rigid; only the posterior end of the body was flexible. The tail was merely an extension of the spine accompanied by a membrane flattened in the vertical plane. From this primitive tail evolved the efficient tails of modern fish.

5b



THE AMMONITES | vanished rulers of the seas

1

The extinction of species has been a common phenomenon of the history of life on Earth. Even forms of life that were widely distributed and represented by many different species have disappeared completely, leaving no direct descendants. One such group, known only from fossils, is the ammonites—large marine mollusks that lived in spiral, chambered shells.

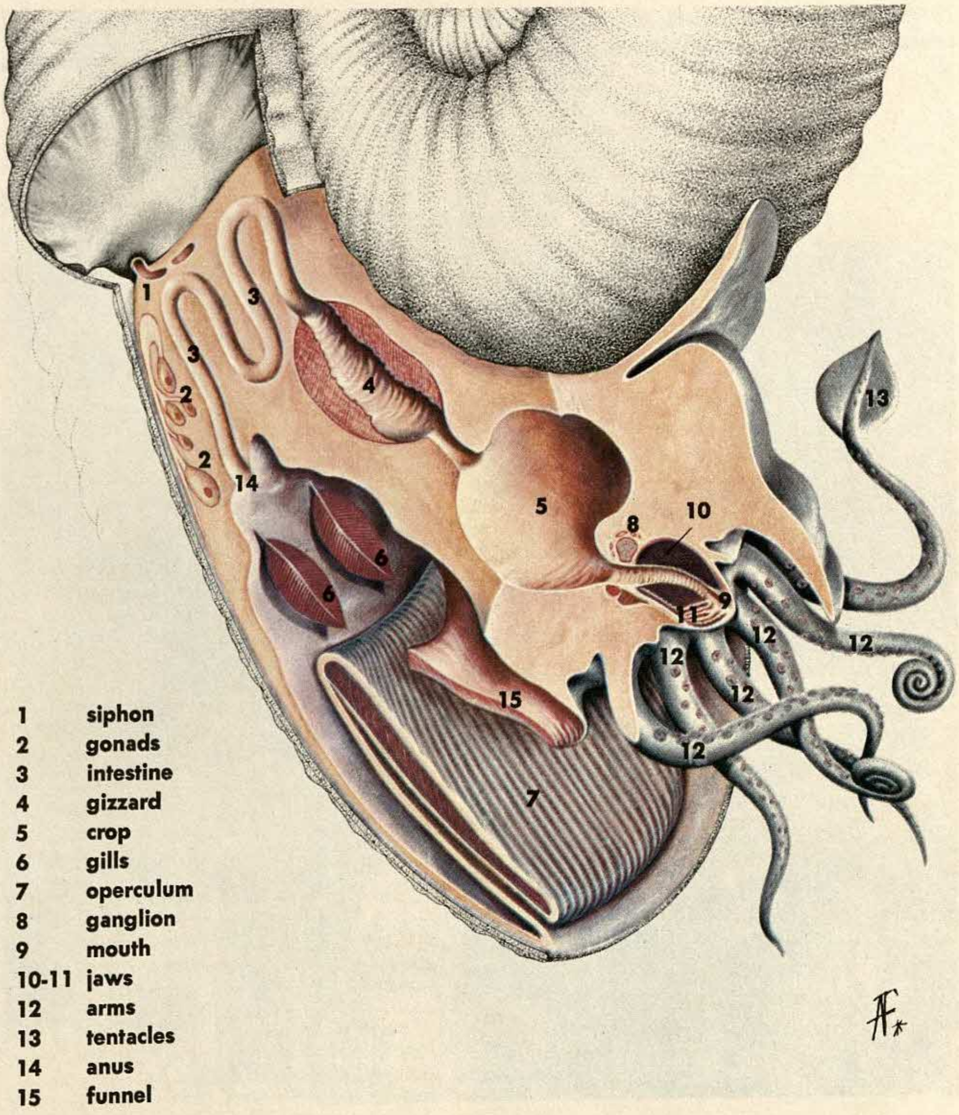
Only the outer shells of the ammonites were preserved. None of the soft parts of the bodies were fossilized, even in fine silts that have preserved traces of much more fragile and quickly deteriorating body parts. The shells are, however, common in rocks found in many different parts of the world. They show a great variety of size, shape, and ornamentation. The largest ammonite shell fossil known—*Pachydiscus seppenradensis,* found in Cretaceous rocks in Westphalia—is about 2 m (about 6.7 ft) in diameter.

The manner in which the animals' bodies were attached to the shells—and this can be deduced from the muscle imprints discovered inside the shells—indicates that they belonged to the class Cephalopoda, along with the octopus, squid, and cuttlefish. Of all animals living today, the one most closely related to the ammonites is the nautilus. Like the nautilus, the ammonites built chambered shells, sealing off old segments as they constructed new ones. The body occupied only the newest, outermost chamber; the sealed-off, inner chambers contained gases that were adjusted to the pressure of water outside the shell, so that the animal could live at any depth of the sea.

The common ancestors of the nautilus and the ammonite were cephalopods of the subclass Nautiloidea, which first appeared during the Lower Cambrian period (about 570 million years ago). By the early part of the Paleozoic era the nautiloids had developed highly specialized forms whose origins are lost much farther back in time. The nautiloids reached their highest development during the Silurian period, when their shells abandoned the primitive straight and arched shapes and assumed the more advanced planospiral shape.

From the Silurian period on, the nautiloids regressed. By the end of the Paleozoic era they were reduced to a single genus, *Nautilus,* which has survived un-

2

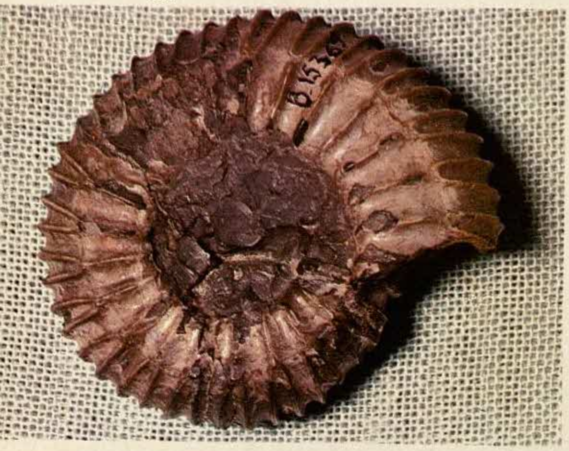


1	siphon
2	gonads
3	intestine
4	gizzard
5	crop
6	gills
7	operculum
8	ganglion
9	mouth
10-11	jaws
12	arms
13	tentacles
14	anus
15	funnel

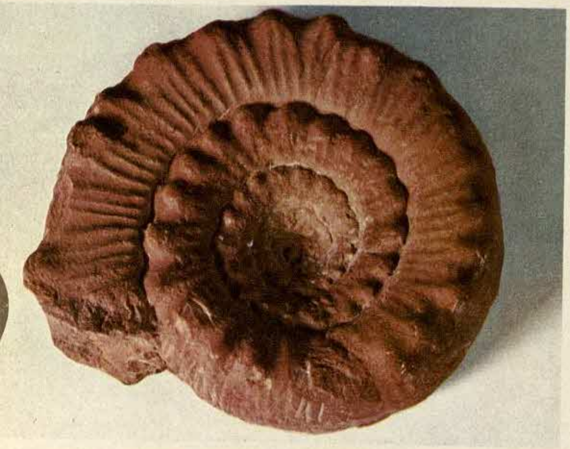
ANATOMY OF THE AMMONITE—This illustration is a hypothetical reconstruction of the soft parts of the body. No ammonite bodies were preserved as fossils, but traces of muscle attachments inside the shells indicate that these animals were cephalopods, and the similarity of their shells to nautilus shells presupposes a similar configuration of the body parts. The ammonite probably had, like other cephalopods, a mouth apparatus encircled by arm-like tentacles. To the sides, above the jaws, were the eyes (not shown). Near the bottom was a large cavity that allowed water to flow toward the gills, where oxygen was absorbed, and into a funnel. The rapid expulsion of water from the funnel propelled the animal backward. The central region of the outer mantle contained a rigid operculum made up of three layers of calcite. Once the animal had pulled itself entirely inside the living chamber, the operculum could be rotated to close the opening in the shell.

AMMONITE SWIMMING IN THE ANCIENT SEA—This artist's conception of a living ammonite is based on the presumed similarity of the ammonite to the nautilus. The species represented is *Hildoceras bifrons,* an index fossil that lived more than 150 million years ago during the lower Jurassic period.

3a

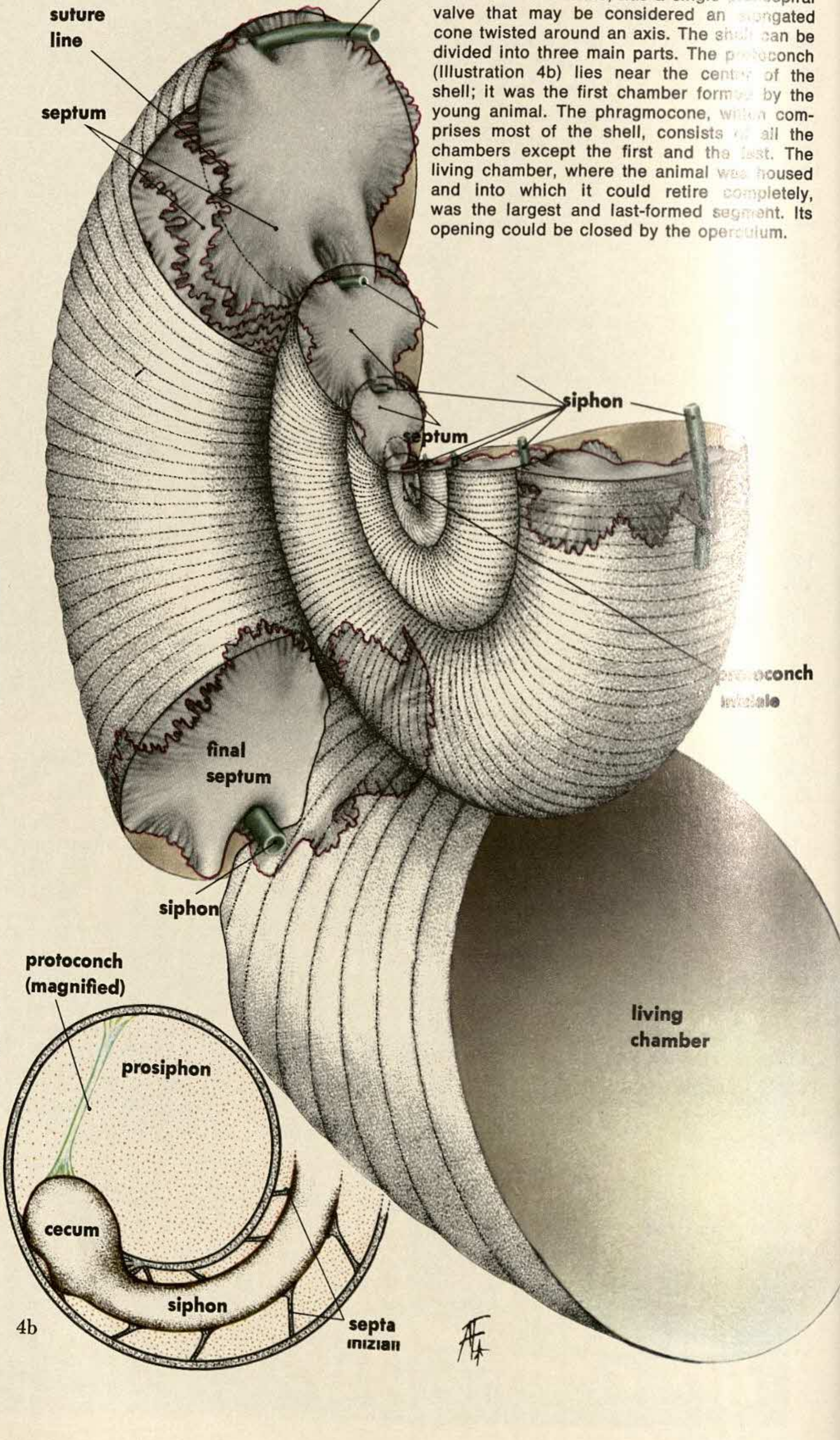


3b

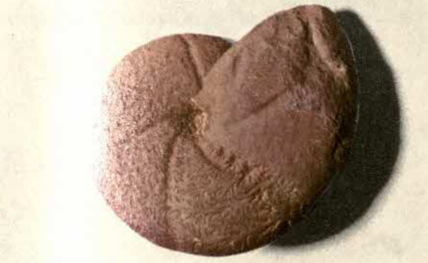


SHELL ORNAMENTATION—The external shells of the ammonites show thin growth lines. Many shells also have radial ribs, tubercles of various shapes and sizes, and spines that must have reached a considerable length in the living organism. In Illustration 3a, each radial rib forks into two prongs on the ventral region. The ornamentation of the shell in Illustration 3b consists of ribs and tubercles. These ornamental variations are useful for purposes of classification; their biological significance is unknown.

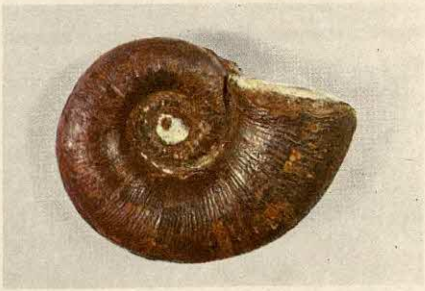
4a **GENERAL SHELL STRUCTURE**—The typical ammonite shell (Illustration 4a), which consists of calcium carbonate, has a single planospiral valve that may be considered an elongated cone twisted around an axis. The shell can be divided into three main parts. The protoconch (Illustration 4b) lies near the center of the shell; it was the first chamber formed by the young animal. The phragmocone, which comprises most of the shell, consists of all the chambers except the first and the last. The living chamber, where the animal was housed and into which it could retire completely, was the largest and last-formed segment. Its opening could be closed by the operculum.



5a

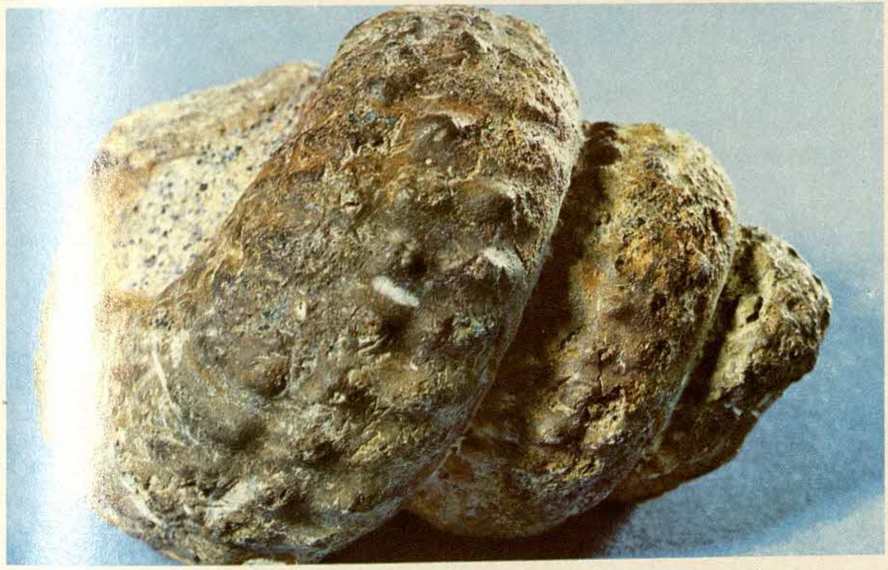


5b



THE SHAPE OF THE SHELL—The ammonite shell was generally planospiral, but the basic plan is that of an elongated cone. The shells of the earliest ammonites were completely straight. From the early Devonian period, through the rest of the Paleozoic era and much of the Mesozoic era, the cones were coiled into the planospiral pattern most typical of the ammonites. Toward the end of the Cretaceous period individual shells began to form as spirals but then straightened out so that they looked something like umbrella handles. Other ammonite shells coiled in three dimensions, and still others were curled in no particular direction, thus assuming random shapes. By the end of the Cretaceous period the ammonites were at the end of their evolutionary progress, and were about to become extinct. *Calliphylloceras* (Illustration 5a) has an involuted shell in which the last twist completely wraps around the others. *Lytoceras* (Illustration 5b) is very primitive; its coils hardly touch each other. *Turrilites* (Illustration 5c) is an ammonite of the Cretaceous period with a shell coiled in three dimensions.

5c

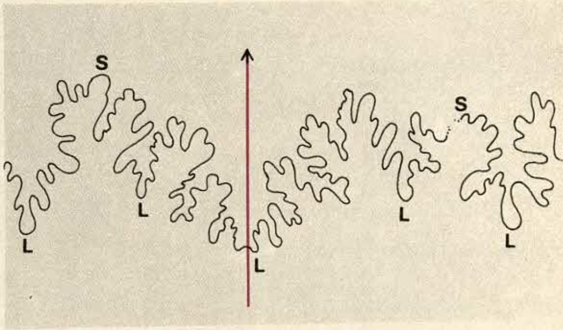


The phragmocone was divided into numerous chambers by the septa, which lay perpendicular to the inner wall of the shell, on which the septa left characteristic wavy lines, the suture lines. This series of chambers formed the floating organ of the animal, the organ used for vertical underwater movement. Like the chambers of the modern nautilus, the chambers of the ammonites were filled with gases whose pressure was regulated by the animal. Each septum had an opening through which passed a slender strand of living tissue, the siphon. The siphon extended from the main mass of the animal's body, in the living chamber, through all the chambers of the phragmocone to the protoconch, where it enlarged into the cecum. This was attached at the base by a calcareous cord, the orosiphon. The siphon regulated the gas content of the phragmocone chambers.

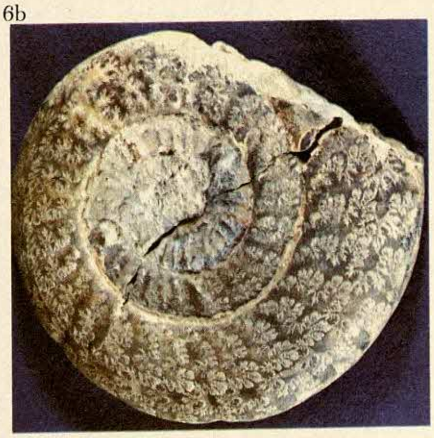
THE SUTURE LINE—The ammonite shell is divided into a number of chambers by walls or septa that leave characteristic insertion lines on the inner surface of the shell. These can be seen clearly when the outer layer of the shell is removed. The suture lines of ammonite shells are highly irregular. In Illustration 6a, a complete suture line has been reproduced in one plane. The arrow points toward the opening of the shell. The lobes **L** are directed away from the opening; the saddles **S** are directed toward it. The suture lines, which varied in the different species, became increasingly complex as evolutionary development progressed. Also, the first sutures formed by an individual animal were relatively simple; later sutures were progressively more complicated.

The function of the complicated structure of the septa is not known, but it may have reinforced the shell, which was very thin, thereby enabling the deep-water species to resist high pressures, and the coastal species to resist battering from wind and waves. The series of suture lines is clearly visible in the specimen (Illustration 6b) from which the external shell has been removed. In this case the lobal line is fairly complex, with a fine leaflike pattern of the *Phylloceras* type.

6a



6b



changed to the present time.

The ammonites first appeared during the Carboniferous period at the time when the nautiloids were highly developed and numerous. As the nautiloids regressed, the ammonites developed vigorously. By the time the ammonites reached their period of maximum development, the nautiloids were nearly extinct.

Although the ammonites were phylogenetically derived from the nautiloids, they were more advanced and better adapted to the environment. No forms intermediate between nautiloids and ammonites are known except for *Bactrites,* a genus of Devonian mollusks that shared some internal characteristics with the ammonites but had straight shells very similar to those of the primitive nautiloids. *Bactrites* seems to be a link between the straight-shelled nautiloids of the Cambrian and Lower Silurian periods and the spiral-shelled ammonites that first appeared during the Devonian period.

The ammonites developed relatively slowly during the Paleozoic era. There were few main groups, but they contained a great variety of forms. The first real evolutionary explosion of the ammonites took place at the beginning of the Triassic period (about 225 million years ago). This proliferation only foreshadowed the enormous development the ammonites underwent during the following two periods (the Jurassic and the Cretaceous).

During the Triassic period the ammonites spread widely throughout all the seas of the world. By the end of that period, however, most species had died out and the ammonites were nearly extinct. A few survived, and a second evolutionary explosion repopulated the seas during the Jurassic and Cretaceous periods. During the Cretaceous period the ammonites went into another decline that was to be their last. Rather suddenly, about 65 million years ago, the ammonites became extinct.

Thus the ammonites appeared during the Carboniferous period and disappeared during the Cretaceous period—a span of more than 200 million years. During that time, about 5,000 different species evolved. Some species lived during only one period or part of one period, but all were widely distributed throughout all seas and at every latitude. It is because of this wide distribution of species that ammonites are the most useful of index fossils, for the presence of this species in a given rock indicates the period in which the rock was formed.

The explosive evolution and the wide distribution of the ammonites poses a question: what were the causes of this development that has no equal in the present-day world? No doubt these organisms appeared at a time that was favorable to them; they were probably better suited to changing conditions than the nautiloids that they superseded. Ammonites seem to have been highly adaptable animals, able to live in deep or shallow seas and in warm or cold climates.

The reasons for the disappearance of the ammonites are unknown. One theory holds that the ammonites were preyed on by the marine reptiles that evolved during the Mesozoic era. Tending to confirm this theory is the presence of ammonite fossils in the stomachs of fossil marine reptiles; other ammonite fossils show the marks of reptile teeth. Another theory holds that during their long evolution the ammonites became too highly specialized to adapt to new changes in the environment.

Ammonites probably fed on smaller aquatic organisms, such as minute crustaceans, as other cephalopods do. It can be assumed that they swam by jet propulsion, forcing seawater through a funnel-shaped organ as do the octopus, the squid, and the nautilus. When swimming, the ammonite held the shell so that the plane of symmetry was vertical and the living chamber was at the bottom. Proof of this swimming position was obtained when ammonite fossils were found in the Jurassic limestone of Bavaria; beside the shells were the imprints they left as they settled onto the mud of the sea floor.

The shells of different ammonite species vary in appearance. Some are laterally flattened, and the resulting disklike shape was probably well adapted to swimming. Because shells of this type are found most often in clay deposits characteristic of the deep sea, it is theorized that these species probably lived in the open sea far from land. Shells with pronounced ridges, spines, and ornate sculpturing are found most often in limestone deposits, and it is theorized that these species probably lived in shallower water near coastlines. It is difficult, however, to determine the environment and habits of a species on the basis of the type of rock in which a fossil is found. This is because the shell may have been transported after the animal died; if the shell became separated from the body at the time of death, the empty, buoyant shell might have been carried a long way by ocean currents and tides. Thus, the species whose shells are found in the rocks of coastal deposits may have actually lived in the deeper parts of the sea, and vice versa.

A factor that has contributed to the difficulty of classifying ammonite fossils is the existence of numerous individual fossils that are quite unlike all others. These odd fossils were sometimes classified as new species when they were, more likely, deformities resulting from injury to the living organism. Numerous fossils show wounds and fractures of the living chamber (the weakest part of the shell) or, less often, of other parts of the shell. When such accidents occurred during an early stage of the organism's life, the result may have been an abnormal growth pattern that produced a deformed shell. Some of these "monsters" have oddly twisted, asymmetrical shapes, while others bear patterns of suture lines or ornamentation quite different from that found on other fossils shells of the same type.

THE CARBONIFEROUS PERIOD | when plants dominated

THE PERIOD OF PLANT DOMINATION—The largest ferns growing today are never more than a few meters high, but during the Carboniferous period the largest ferns competed in size with the tallest plants. The photograph (preceding page) shows a small specimen of *Pecopteris miltoni*, a plant characteristic of the Carboniferous period. Due to the fine texture of the sediment from which the enclosing rock was formed, this specimen reveals even the finest details. Plant fossils of the Carboniferous period are abundant and often well preserved; they provide scientists with a broad knowledge of their structures and with an appreciation of the composition of the luxuriant forests of this period.

About 340 million years ago a great marine transgression began that eventually covered the area occupied today by the British Isles. This event marked the transition from the Devonian period to the Carboniferous period. During the Carboniferous, which lasted for about 100 million years, the continents were populated by plants to an extent that has never been equaled up to the present time.

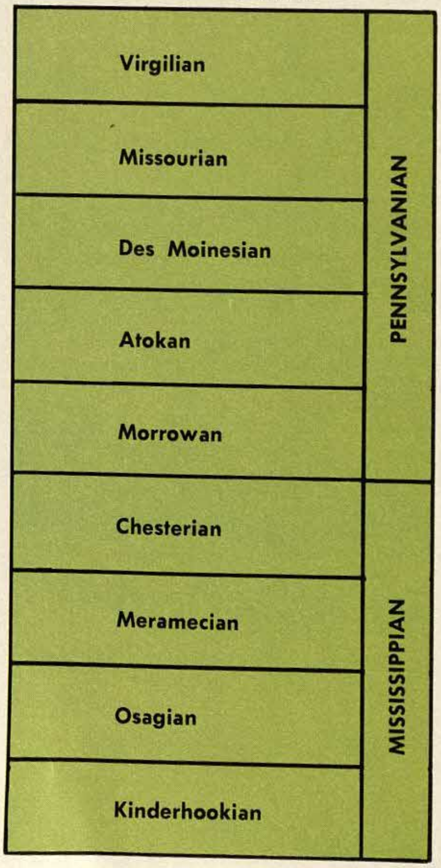
During the Silurian period some species of plants began to make the transition from aquatic environs to terrestrial surroundings; during the following period, the Devonian, woods appeared. Finally, during the Carboniferous, the woods developed into true forests. It is impossible to explain fully why plants proliferated to this extent, leaving enormous deposits of carboniferous remains, which in time were transformed into coal. Not all of the coal in the Earth's crust was formed during the Carboniferous period, of course, although a large portion of this valuable material was formed then. For this reason, scientists think that the atmosphere of the Carboniferous must have been especially rich in carbon dioxide, an essential substance for plant metabolism; but it is impossible to prove that this was the cause of the colossal bloom of the plant world.

The history of the variations in the level of the seas during the Carboniferous is complicated because the period spanned such a great length of time.

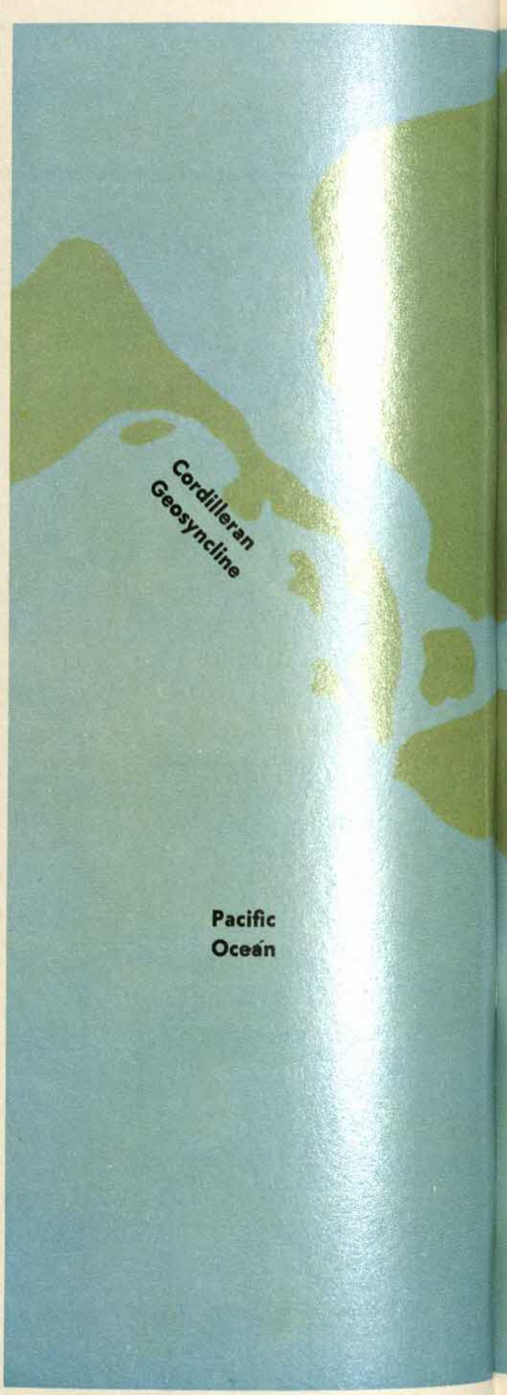
SUBDIVISIONS OF THE CARBONIFEROUS—The Carboniferous period has been subdivided in various ways in different places around the world. The rocks comprising the Carboniferous system have been subdivided into series corresponding to both plant and marine fossils.

In North America, the Carboniferous is considered as two distinct periods, known as the Mississippian and the Pennsylvanian. The Mississippian, which began about 340 million years ago, corresponds approximately to what is known in Europe as the Lower Carboniferous or Dinantian; the Pennsylvanian, which began about 300 million years ago, corresponds roughly to the Upper Carboniferous.

Rocks of the Mississippian System have been classified according to marine fossils, into four series; the Kinderhookian, the Osagian, the Meramecian, and the Chesterian. These series names have been derived from place names in the midwestern United States. Rocks of the Pennsylvanian system have been subdivided into five series: the Morrowan, the Atokan, the Des Moinesian, the Missourian, and the Virgilian. This classification is also based on marine fossils; however, another classification, based on plant fossils, is sometimes used in subdividing the Pennsylvanian. In Europe and elsewhere, still different names have been assigned to the various rock series, and these series do not always correspond to the series recognized in the United States. A classification devised for use in one general area does not always lend itself to application in other geographic regions. The task of subdividing the Carboniferous attests to this conclusion.

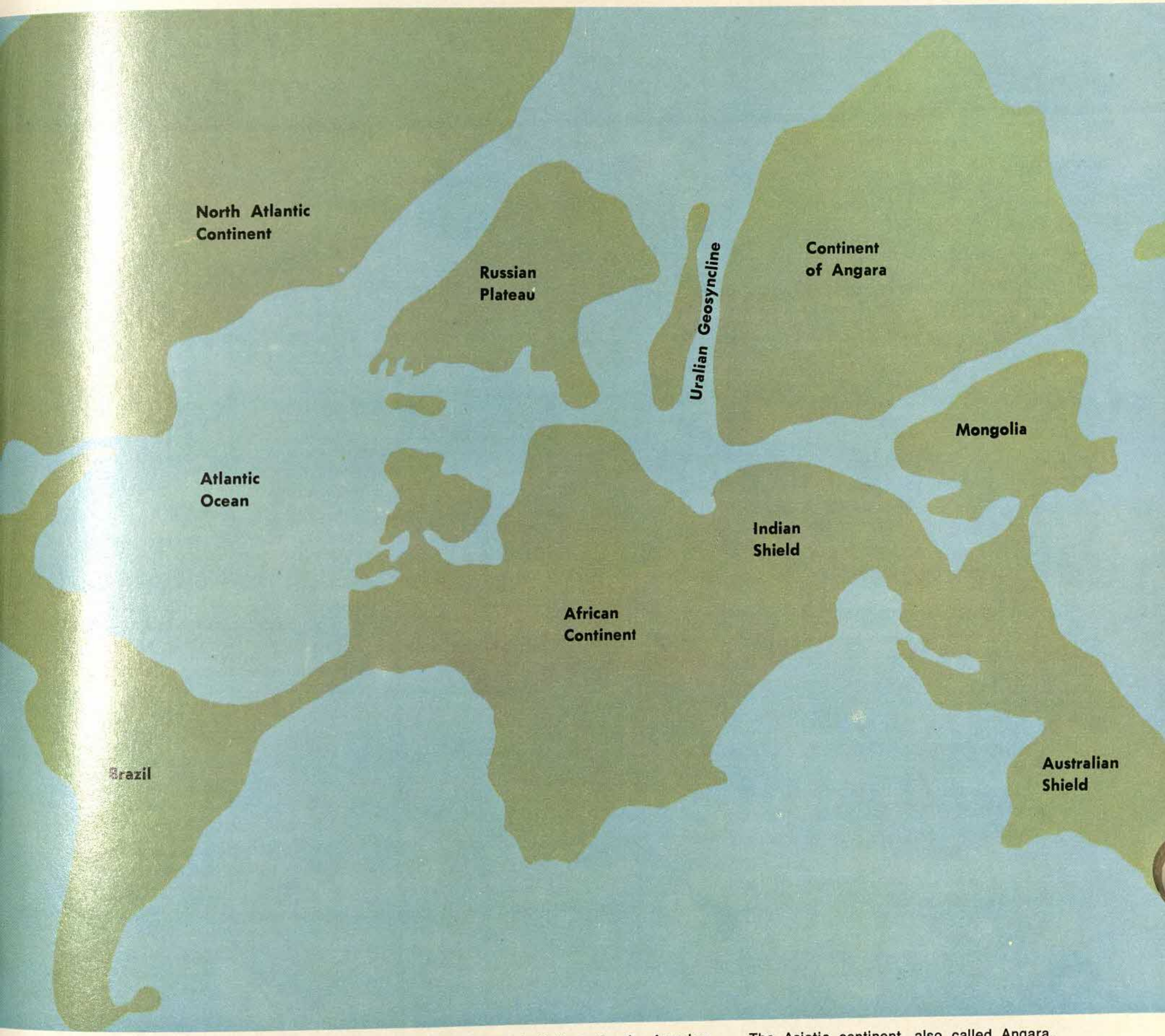


Virgilian	PENNSYLVANIAN
Missourian	
Des Moinesian	
Atokan	
Morrowan	
Chesterian	MISSISSIPPIAN
Meramecian	
Osagian	
Kinderhookian	



THE CARBONIFEROUS PLANISPHERE—It is difficult to summarize in a single planisphere all the situations that occurred during the Carboniferous period, a span of some 100 million years. Nevertheless, in brief, three continents existed, one in the North Atlantic, another in the Southern Hemisphere, and still another corresponding to present-day Asia.

The North Atlantic continent had practically

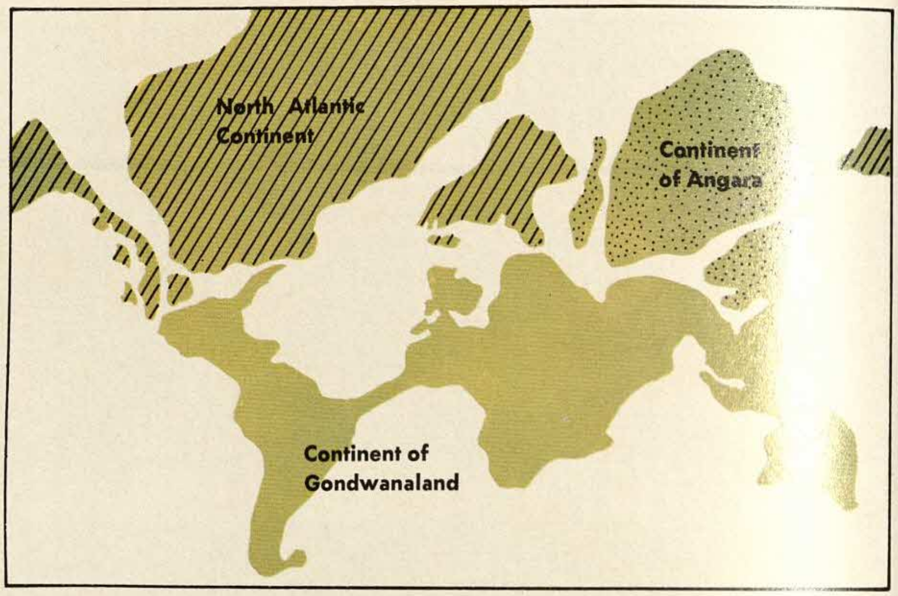


the same shape as it had in previous periods. Whether or not it was already separated by a narrow stretch of sea corresponding to the North Atlantic Ocean of today is uncertain. The cordilleran geosyncline was present throughout the period, separating the present-day Rocky Mountains from the Pacific Ocean.

The southern continent, called Gondwanaland, was formed by the union of all the southern lands, including South America, Africa, the Arabian Peninsula, India, Indonesia, and Australia. The Tethys Sea, separating Gondwanaland from the dry lands of the north, stretched across a region that today includes parts of the Atlantic Ocean, the Mediterranean Sea, and the Middle East as far as the Himalayan Mountains. Widespread glaciation occurred in Gondwanaland.

The Asiatic continent, also called Angara, corresponded to present-day Siberia; during the Carboniferous, the climate there was warm enough to support a luxuriant flora. Angara was bordered on the west, south, and east by geosynclinal seas. The sea on the west, which separated Angara from the North Atlantic continent, was formed by the great Uralian geosyncline.

FLORA OF THE CARBONIFEROUS PERIOD—This map shows the distribution of Carboniferous flora. Basically, four great floristic regions existed: that which was characteristic of the North Atlantic continent, called the Euro-american province; that which was found with constant, well-balanced associations in all the southern regions, called the province of Gondwanaland; and that which was characteristic of present-day East Asia, subdivided into the province of Angara in the north and the province of China in the south. The flora of the latter were widespread, covering the region corresponding to the part of China that is on the same latitude as Korea. The flora also appeared sporadically in the southern part of Angara, but scientists have hypothesized that this region underwent very intense movements, sinking into and emerging from the sea. In other words, it is believed that the southern part of Angara was connected at times with the Siberian continent and at other times with the continent of Gondwanaland. The biological evidence from the Carboniferous period is used to support the hypothesis that Gondwanaland was first united.



Many regions of the Earth were completely submerged, only to re-emerge later; some regions were inundated many times. Complex orogenic changes also took place, and these changes were accompanied by plutonic and volcanic activity.

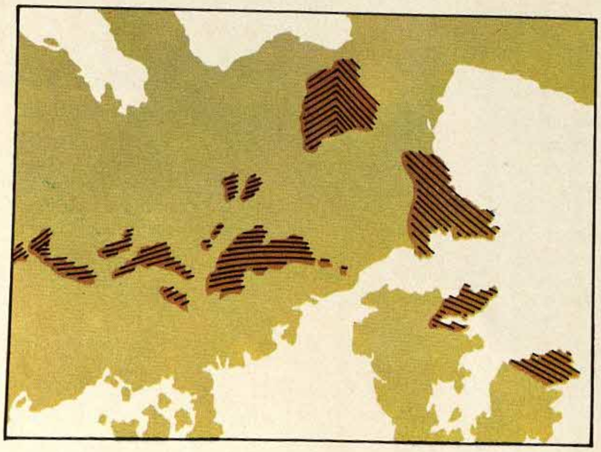
The fact that the climates were different from those of today is not surprising, but what is remarkable is that, on the continent of Gondwanaland (which then encompassed South Africa, South Asia, South America, and Australia), widespread glaciation took place. On the other hand, regions that now have glacial climates, such as the Spitsbergen Islands, were characterized by mild climates, which favored the formation of coal deposits.

The name "Carboniferous" is derived from the widespread coal deposits that were formed during this time in Earth history. Coal is also found in deposits that were formed both before and after the Carboniferous period—in fact, coal is still being formed today—but it seems that the speed of formation that characterized the Carboniferous period has never been repeated.

Naturally, coal deposits are not found in all the rocks formed during the Carboniferous period, although they are found in all Carboniferous rocks of certain regions, such as China. In the mountainous regions of western North America, however, widespread Carboniferous features contain no coal. Coal from the Carboniferous is among the best that can be found, because it is neither too young nor too old; young coal has a low heating capacity, while coal that is too old may already have been partly transformed into graphite, a substance that is difficult to burn.

During the Devonian period, when the fishes were abundant in the seas, amphibians made their appearance on the Earth. The beginning of the Carboniferous period marked the appearance of the first insects with incomplete metamorphosis. On different parts of the Earth where certain plant forms predominated, forests were forming. Halfway through the Carboniferous, the conifers appeared, and their line has survived to the present day.

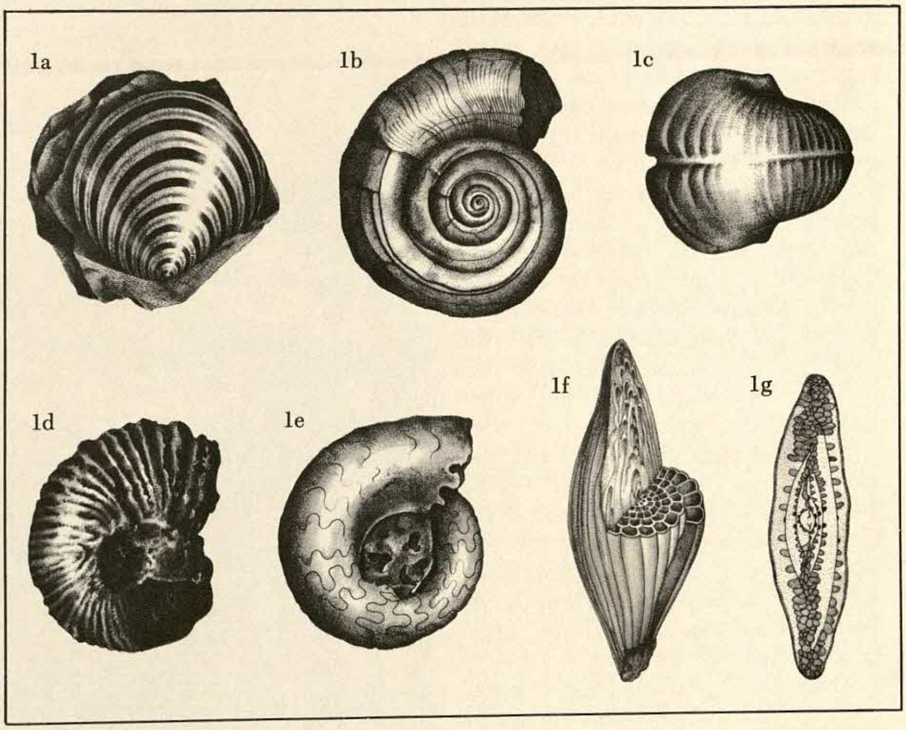
Early forests developed almost entirely in swamplands. Water, therefore, was still an extremely important element for the development of Carboniferous plants. It was probably also the determining factor in the formation of the coal deposits that typify this period.

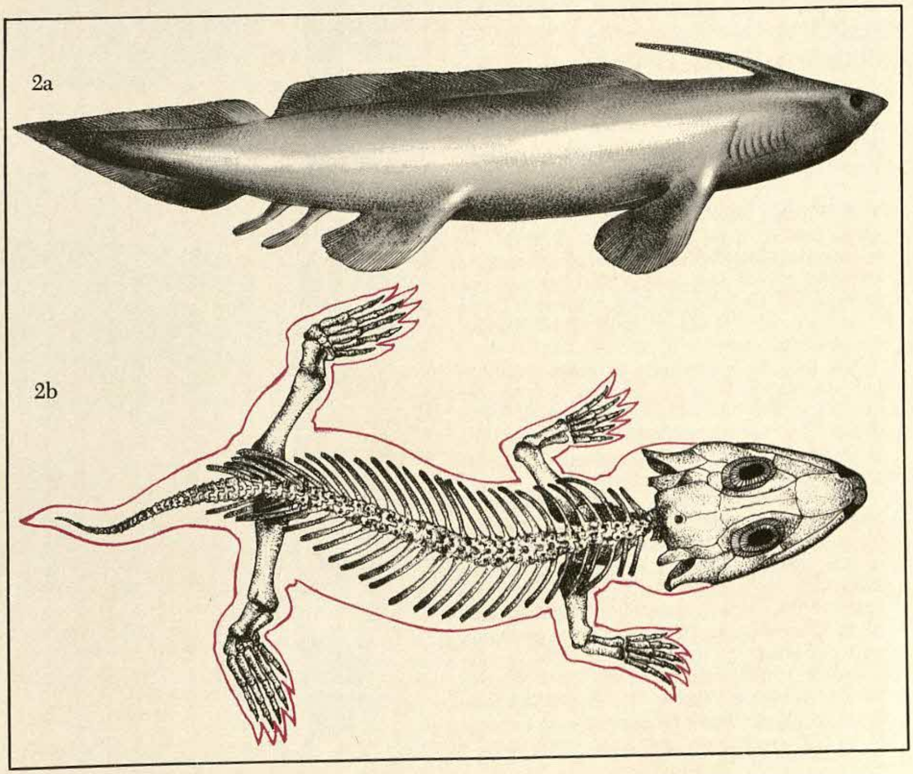


THE HERCYNIAN OROGENESIS—Orogenic phenomena occurred in different parts of the Earth during the Carboniferous period. In Europe this period of ancient mountain building has been called the Hercynian or Variscan Orogenesis and, as the map shows, it affected southern Ireland, the southwestern part of England, Brittany, the Massif Central in France, the Vosges, the Black Forest, the Ardennes, and the Erzgebirge or Ore Mountains. The dark lines drawn through these areas on the map indicate the direction perpendicular to which the orogenic forces acted; it may be observed that these forces acted in different directions in Central Europe and in the regions farther south. The orogenic phenomena were accompanied by intense magnetic phenomena. In Europe, magma rose from the depths of the Earth and solidified under the surface, forming plutons. Among the best known of these intrusive rock formations is the one that forms part of the massif of Mont Blanc. Another famous intrusive rock originating during the same time span is that of the massif of Saint Gotthard in the Swiss Alps.

FAUNA OF THE CARBONIFEROUS PERIOD

the continued evolution of animal forms





LOWER FORMS OF LIFE—The number of lower species of living organisms increased enormously during the Carboniferous period. Of the huge number of forms, some evolved greatly, others evolved very slightly, and still others disappeared altogether in a relatively short period of time.

The forms that appeared and became extinct within a few million years are of special interest to earth scientists, because they function as guide fossils, serving to identify rather accurately certain epochs and ages. Suppose, for example, that a certain species lived for a certain length of time, from 300 to 200 million years ago, and that another species lived between 240 and 150 million years ago. (Actually, the limits within which species lived are identified by the names of the epochs.) If scientists find the two species together in the same rock sample, they can conclude that the enclosing rock was formed during the span common to the two organisms—that is, between 240 and 200 million years ago. In some cases the time span can be reduced further, as, for example, when the parts of the epochs that the two specimens had in common are narrower, or when the association consists of more than two species. Tiny fossils are numerous, diversified, and widespread in Carboniferous rocks. Through a study of these fossils, it is possible to measure the percentage of various species, to determine the age of the enclosing rock, and to discover many facts about the environment in which the Carboniferous organisms lived.

Lower forms of Carboniferous life shown in this illustration include a specimen of *Posidonia becheri,* a pelecypod (Illustration 1a); two gastropods, *Euomphalus* (Illustration 1b) and *Bellerophon* (Illustration 1c); two ammonites, *Pericyclus princeps* (Illustration 1d) and *Pronorites* (Illustration 1e); and two typical foraminifers or shelled protozoa, *Fusulina* (Illustration 1f) and *Schwagerina* (Illustration 1g).

FISH AND AMPHIBIANS—During the Carboniferous period, the fish continued the evolution they had begun during the Devonian period; cartilaginous, sharklike animals abounded in the Earth's waters. The amphibians evolved toward the forms that would soon become characteristic of the saurians or lizardlike reptiles.

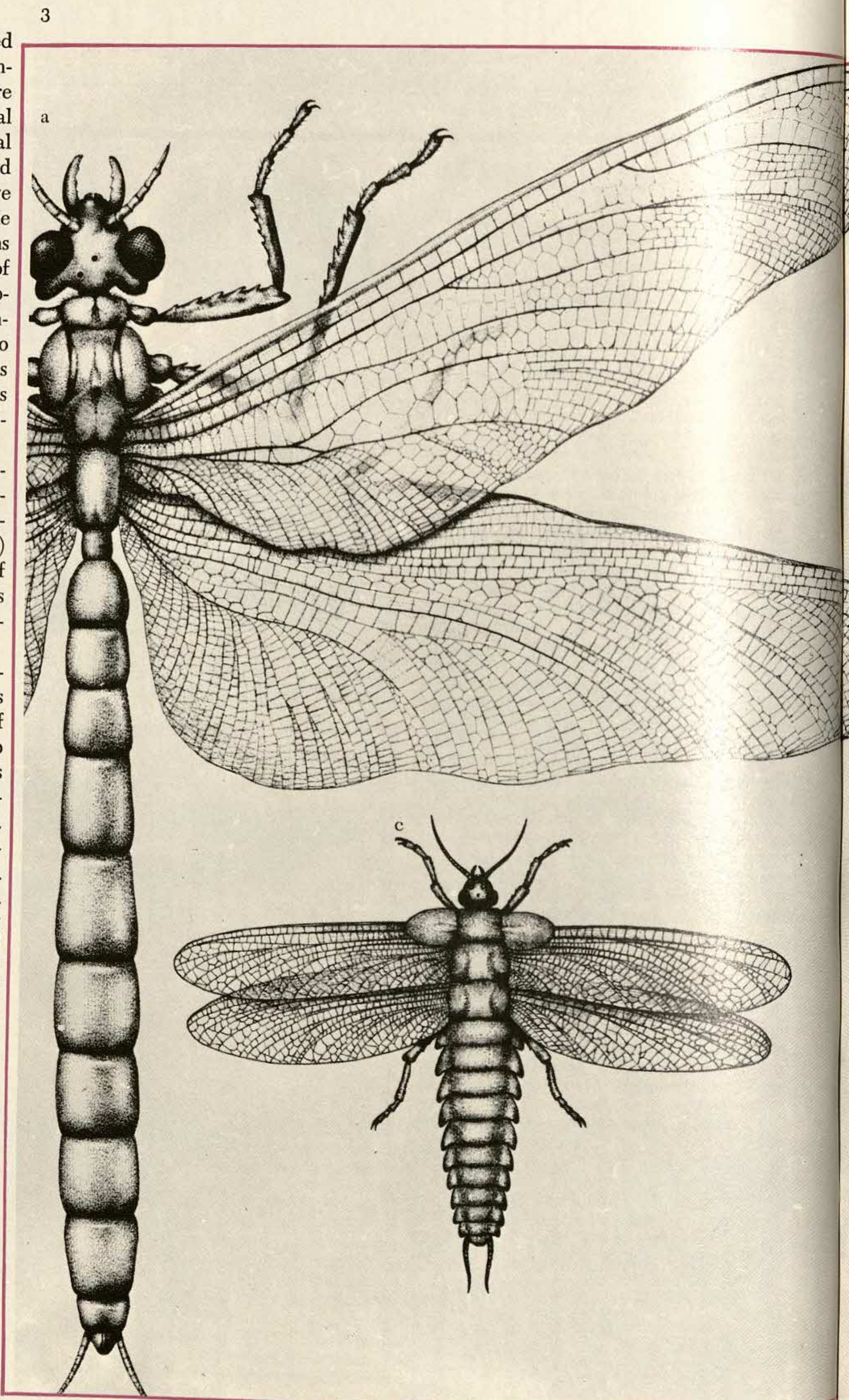
The form of *Pleuracanthus* (Illustration 2a) was still not very well defined. In particular, the caudal region had not yet evolved into the characteristic fin, which in later fish came to function as the chief organ of motion. Instead, the entire back was covered with a long, low fin stretching to the rearmost extremity of the body; in due time this part was to be transformed into a caudal fin.

It is possible to reconstruct the outline or profile of an organism on the basis of what is known of its skeleton. Generally such a reconstruction takes into account the fact that, if a skeleton was robust, it was subjected to rather strong muscular forces and the muscles must have had corresponding dimensions. In this way it is possible to reconstruct the form of the body. Such a reconstruction has been made in the case of *Diplovertebron* (Illustration 2b). In this animal the limbs adapted to land movement were of substantial size, and, judging from the length of the toes, the limbs were also used for swimming. Limbs of later saurians did not differ greatly from these.

A great number of animals characterized the Carboniferous period. Lungfish, amphibians, reptiles, and many insects were typical representatives of the animal world during this time of the great coal forests. Life in the ocean demonstrated the powerful phenomenon of adaptive convergence; the forms that occupied the Earth's waters were similar to the forms observed today. Another characteristic of this period was the enormous development of the mollusks; in fact, the number of mollusk species multiplied so greatly and their association with this period was so characteristic that it is possible to use the fossil remains of mollusks for dating purposes.

In addition to the forms that progressed, some forms regressed. For example, many species of trilobites (including the once numerous *Phacops*) were becoming extinct; the process of extinction of these marine crustaceans became very rapid during the subsequent period, the Permian.

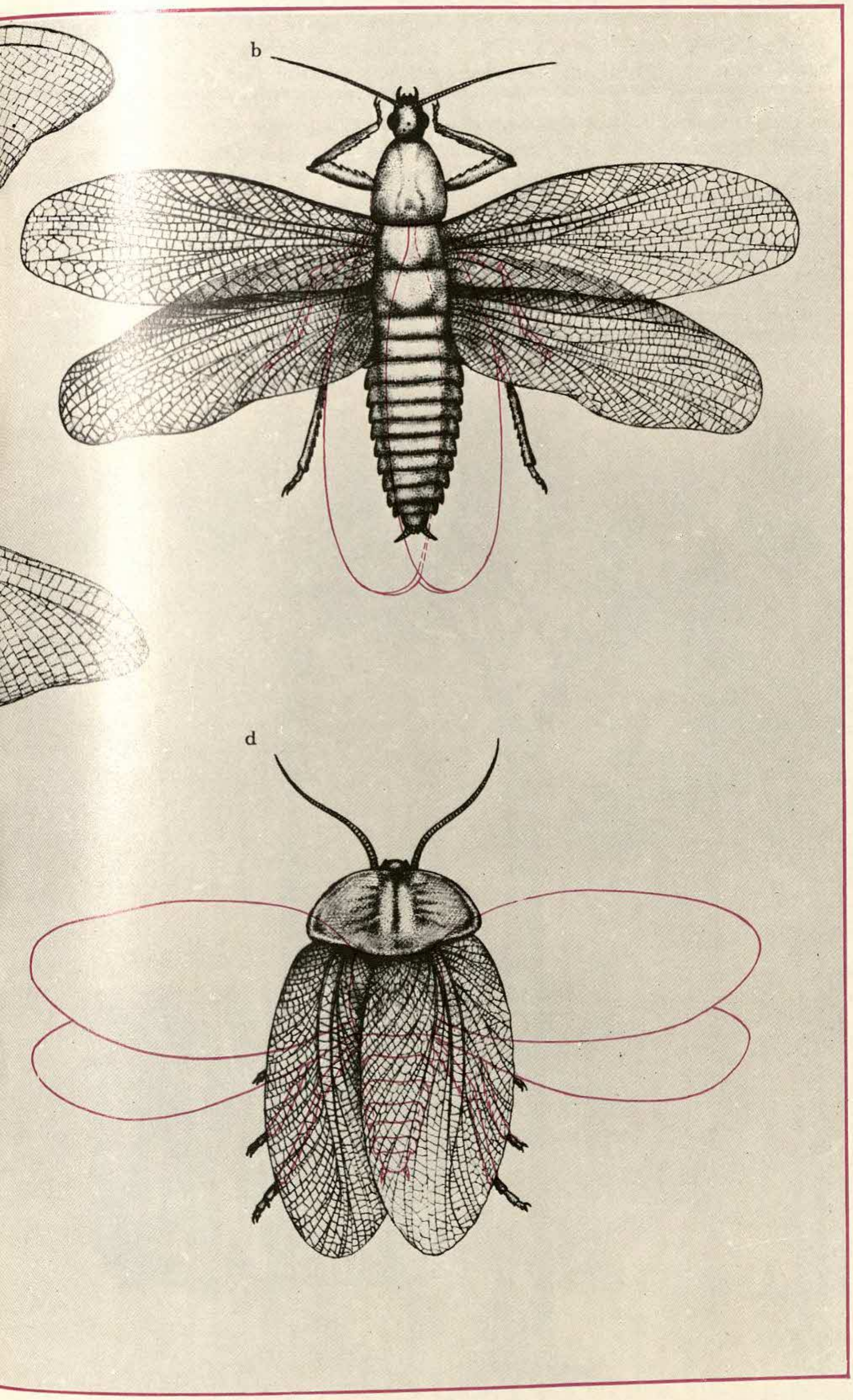
Along with a restricted series of mollusks, crustaceans, and rare eurypterids (related to the king crabs), a wealth of fishes lived in fresh waters. A group of large freshwater predatory sharks was represented, but bony fishes were dominant in Carboniferous period fresh water. The primitive ray-finned fishes (palaeo-



THE FLYING INSECTS—During the Carboniferous period, living organisms took to the air for the first time. The insects of this period required only a few million years to become established, and already they possessed forms nearly as highly evolved as those of present-day insects.

The insects represented in these drawings include *Meganeuron* (Illustration 3a), *Eucoenus* (Illustration 3b), *Stenodictya lobata* (Illustration 3c), and *Mylacris* (Illustration 3d). The latter bore slightly less resemblance to present-day insects than the others.

Meganeuron possessed a form highly reminiscent of a modern dragonfly. It was, however, much larger than any living insect; this noteworthy specimen had a wingspan of 65 cm (about 25 in.), compared with the 20-cm wingspan of the largest dragonfly living on Earth at the present time. From the shape, structure, and placement of the wings, it must be deduced that the dragonfly of the Carboniferous period possessed flying abilities similar to those of the modern dragonfly; it was capable of fast flight as well as slow flight, and it could hover in the air.



niscoids), mostly of modest size, had spread out into a number of genera.

During the Carboniferous, insects such as the primitive dragonflies appeared, and a new system of locomotion—flight—was developed. It must be remembered that, the smaller an animal is, the less is the muscular exertion needed to keep it in the air. For this reason, even though the largest Carboniferous flier had a wingspan of about 75 cm (about 30 in.), it weighed considerably less than a man —who cannot fly through the use of his own muscles. An insect, because of its structure and its very low specific weight, may attain a high level of aerial performance.

To fly is to dominate the air. Unlike water, air contains no floating nutrient materials. However, from the point of view of survival, flying offers a great advantage; air provides very little resistance to motion, compared with the resistance furnished by water or even by land. Therefore, a flying animal may be able to reach a site of abundant food or a place where reproduction can occur much more easily than can an animal restricted to an aquatic or terrestrial existence. Later on, in the course of evolution, the supremacy of flying insects was challenged by other kinds of flying animals; as a result, the insects were subjected to a very rigorous selection process that brought about important species changes.

Amphibians, which first appeared during the Devonian period, continued their development. Most of the amphibians were small, but a few were as large as modern crocodiles. The form of the amphibian body was approaching that of the saurians or reptiles that would come to dominate the Earth during the Mesozoic era. Indeed, reptiles had made their appearance by the latter half of the period. Fossils of most Carboniferous land vertebrates come from the coal swamps, and little is known of what went on in higher and drier places; but some specimens show that reptile evolution had begun. There are even a number of forms pertaining to the Pelycosauria, most ancient of mammalian ancestors.

FLORA OF THE CARBONIFEROUS PERIOD

plants of the coal forests

Following their cautious appearance on land during the Silurian period, plants underwent a tremendous development during the Carboniferous—a development never equaled in subsequent periods. Plant organization, being relatively simple, probably played a major part in this development. Plant physiology is limited to essentials, with nutritional requirements being derived directly from the soil and the atmosphere. Plants need no specialized organs to provide locomotive and hunting capabilities.

Above all, the structure and physiology of plants facilitated their transition from underwater life to a subaerial existence. This transition took place rather rapidly because plants, unlike animals, were able to live partly in, and partly out of, water; for example, many plant species had their roots under water and their upper parts exposed to the air. Such organisms then had the advantages of both types of environmental relationship.

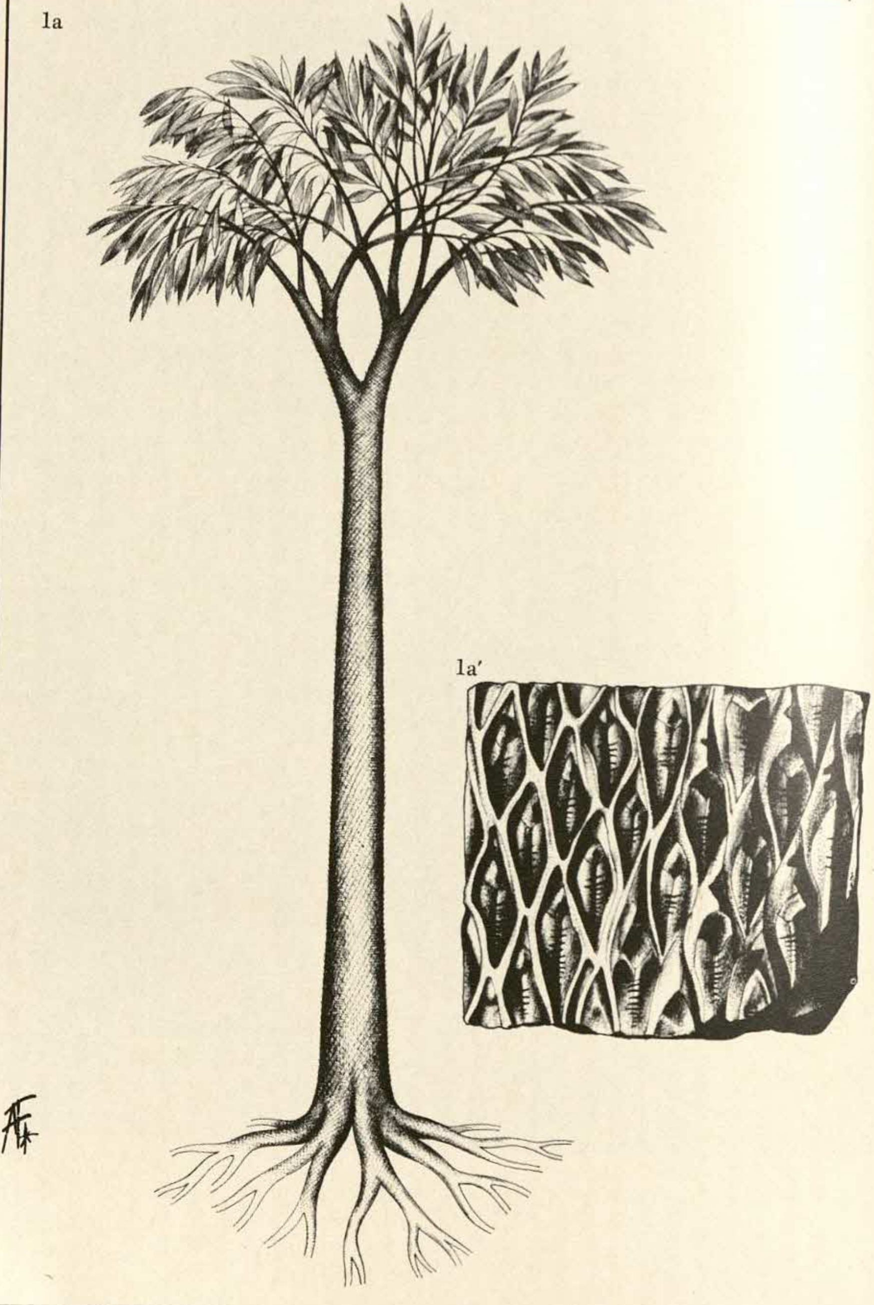
Another important factor was the primitive system of spore reproduction in plants, a system that closely bound the plants to an aquatic environment. In spore-producing plants, the male and female organs are differentiated; the motile male germinal elements require a fluid medium in order to reach and fertilize the female elements. Therefore, in order for reproduction to occur, it is very important for the germinal elements to be released into a suitable medium in the environment. Typically, the organism produces great numbers of spores, thereby enhancing the opportunities for promulgating the species.

Reproduction by means of spores is reminiscent of the reproduction of the monocellular organisms that depend on a fluid environment for their movement and food. Spores are adapted to diffusion in air or in water; they are so tiny that the slightest breeze is enough to pick them up and carry them off. Reproduction by spores, however, is an efficient system only so long as the plants are growing under favorable environmental conditions—that is, in an aquatic environment. As soon as these conditions become rather less than favorable, the inadequacies of the system become evident. Undoubtedly this happened when plants began to live in a subaerial environment, for it was after the transition to land that a new means of reproduction evolved.

The new reproductive system involved the production and distribution of seeds. A seed consists of an embryo plant and nutrient material that enables the new plant to survive during the early stages of its development. The embryo plant and nutrient material are enclosed by a

GIANTS OF THE CARBONIFEROUS PERIOD— All living organisms, whether animals or plants, seem to evolve toward gigantic forms. During the Carboniferous period, gigantic plants appeared for the first time in large numbers. Some of the characteristic giant forms are illustrated here.

Lepidodendron (Illustration 1a), a lycopsid of enormous dimensions, typically attained a height of 30 m (about 100 ft). The forms of *Lepidodendron* and the other plants shown in these drawings were primitive; nevertheless, the salient structural features of the trunks and branches had already been outlined and, in some cases, were quite evident or even exaggerated. Plants like *Lepidodendron*, furnished with an umbrella of branches with small leaves, were probably not subject to great wind pressures. Nevertheless, the roots exhibited a highly accentuated development



protective seed coat. In the course of evolution, seed coats eventually became very hard and resistant to heat, cold, and moisture loss; they became adapted in various ways that facilitated their transportation far from the places where they were produced. The adaptations included structures that served to increase a seed's surface area and to lower its specific weight so that it was light enough to be carried by the wind. Again in time, some seeds developed in ways that attracted the attention of certain animals, but that made them indigestible. As a result, such seeds could be carried far from their places of origin before they were eliminated by the animals. Widespread dispersion of the species was obtained in this way.

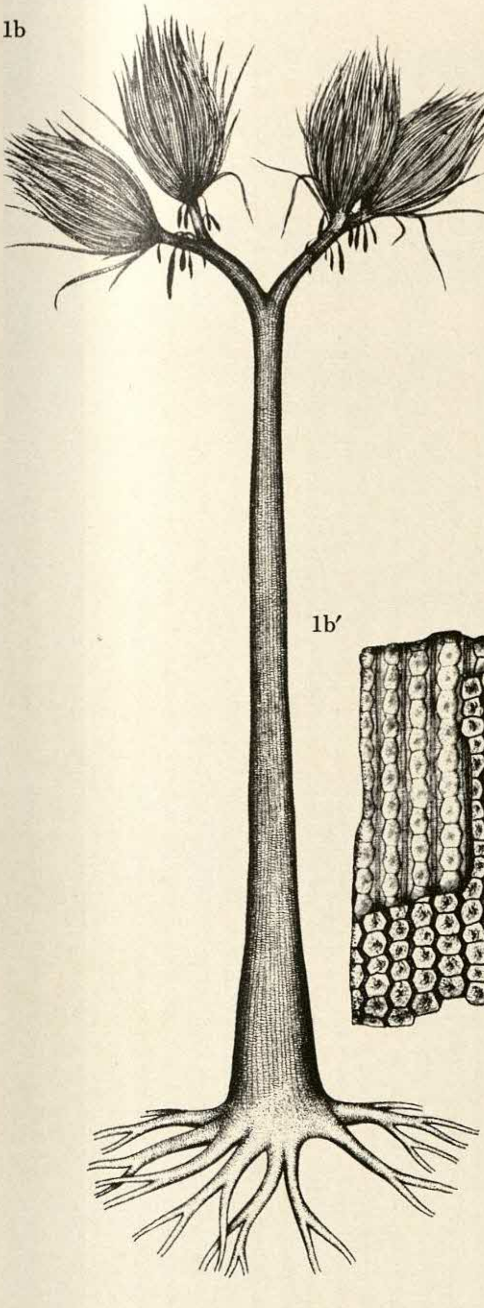
It is easy to think of a Carboniferous forest as being similar to a present-day forest, especially if consideration is given to the majestic height attained by Carboniferous plants. However, although the plants reached a height of 25 to 30 m (about 80 to 100 ft), their structures remained primitive. Branches were scarcely developed, and the reproductive systems were still much like those developed in aquatic environs. Some of these primitive plants exist today, but have much smaller dimensions; for example, modern ferns rarely attain a height of more than 3 m (about 10 ft). Ferns of the Carboniferous forests had thick trunks and were exceptionally tall.

and the trunk was quite wide at the base. Leaves were attached to both the trunk and the branches; when dead leaves dropped off, scars were left where the leaves had been attached. The leaf scars of *Lepidodendron* had a very distinctive pattern (Illustration 1a′).

The trunk of *Sigillaria* (Illustration 1b) measured 2 m (about 6 ft) across at the base, and even larger trunks, some reaching a diameter of 3 m (about 10 ft), are known. The form of *Sigillaria* was even more primitive than that of *Lepidodendron*. Although this plant grew to a great height and had well-developed roots, it generally lacked wide-spreading branches; indeed, its branching was much inferior to that of *Lepidodendron*. The trunk of *Sigillaria*, like that of *Lepidodendron*, was marked by a beautiful and distinctive pattern of leaf scars (Illustration 1b′).

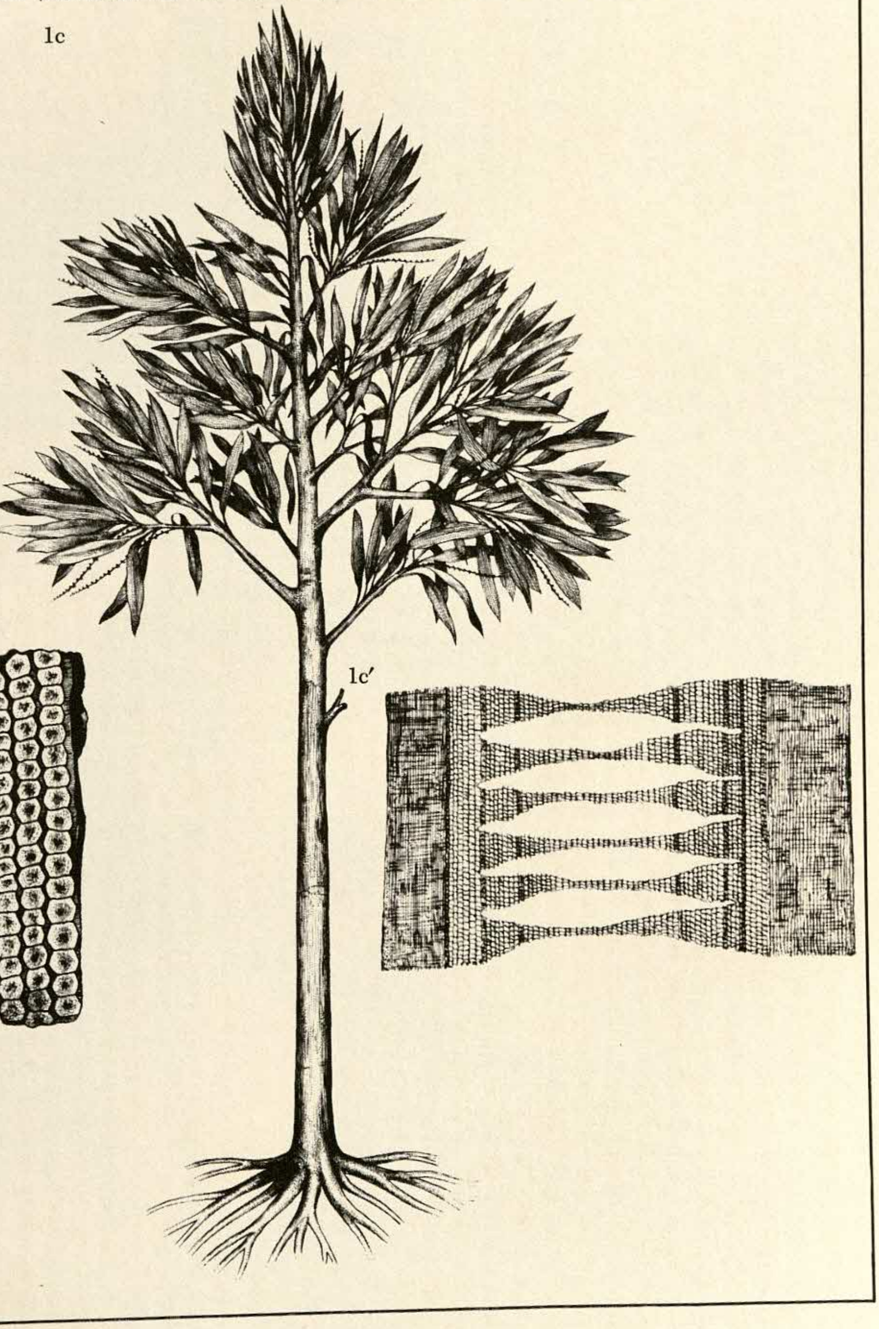
Cordaites (Illustration 1c) was one of the first gymnosperms to make its appearance on the Earth. Its dimensions were less grand than those of the two lycopsids shown in the drawings, but its treelike structure was better outlined, and its simple but extensive ribbon-shaped foliage was arranged in spirals. The branches were covered with highly differentiated leaves. Microscopic observations reveal that the trunk had a wood structure (Illustration 1c′) similar to that of the conifers.

1b



1b′

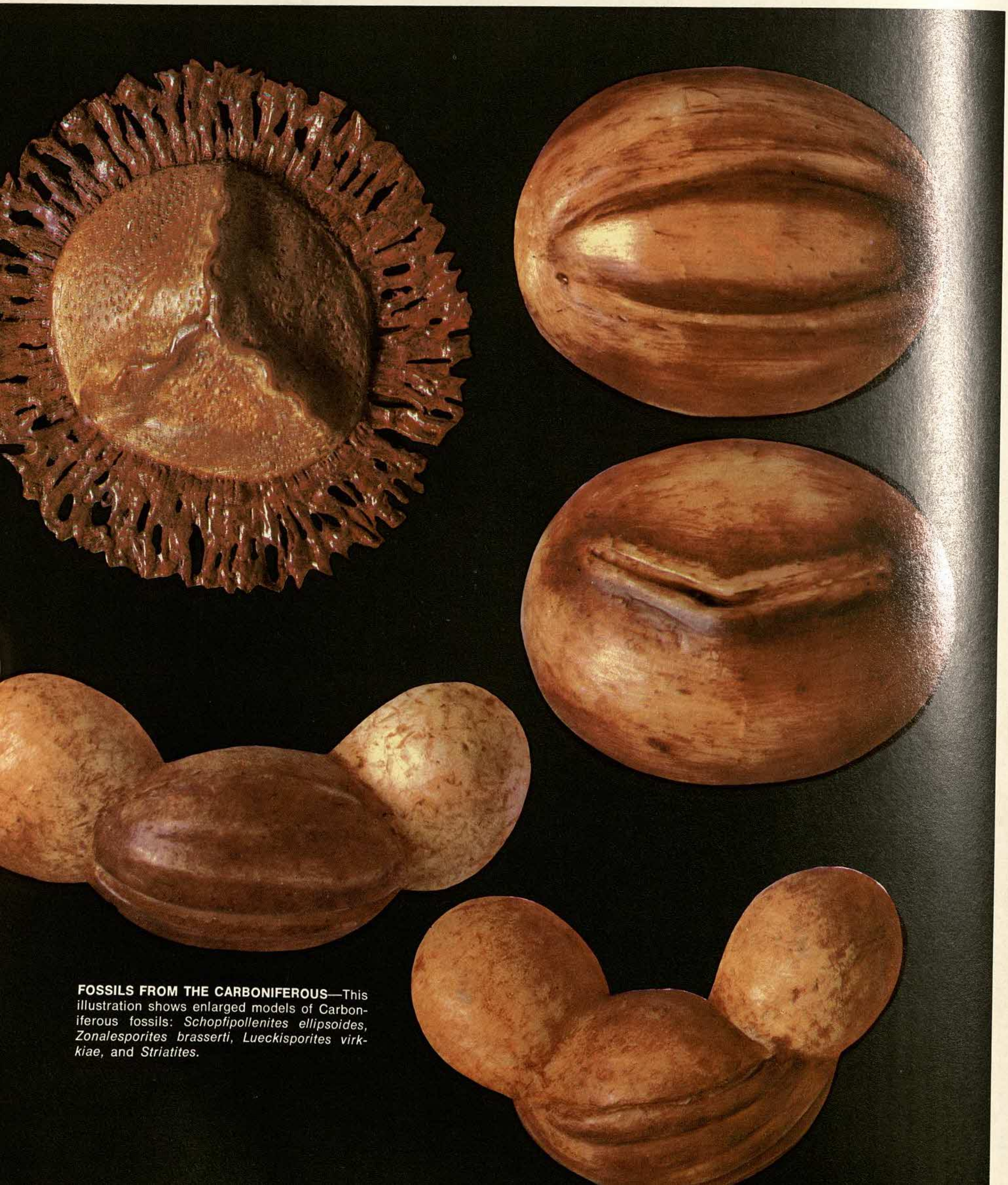
1c



1c′

THE DISTRIBUTION OF CARBONIFEROUS FLORA

clues to an ancient environment



FOSSILS FROM THE CARBONIFEROUS—This illustration shows enlarged models of Carboniferous fossils: *Schopfipollenites ellipsoides*, *Zonalesporites brasserti*, *Lueckisporites virkkiae*, and *Striatites*.

The more specialized an organism, the easier it is to define the environmental conditions under which it lives. Studies of the Pennsylvanian period have provided examples of numerous organisms which characterized climates and environmental conditions of the seas and dry land. A biological climate indicator, the diffusion of corals, has been used to describe the climate of the Silurian seas. Corals, of course, are typical of warm seas, and no species resembling them has ever lived in cold or even cool waters. During the Silurian period corals were present in the seas that are today known as the Arctic Ocean and the sea of the Sunda Islands, as well as in waters adjacent to the southern regions of Australia, South America, and Africa. This fact leads scientists to conclude not only that the seas were warm, but also that they probably had tropical climates.

The distribution of flora also permits scientists to reconstruct the climates of the Pennsylvanian period; complex plants existed during that period and were distributed in different zones, each characterized by a typical flora. Plants began to invade the emerged lands during the Silurian; however, the only information available on the climate of that period is the temperature of the seas and scattered evidence of glacial deposits.

The important point, however, is that plant forms actually did appear on the continents. Then, during the Devonian period, land plants started to become specialized, and afterward, in the Mississippian and Pennsylvanian periods, spe-

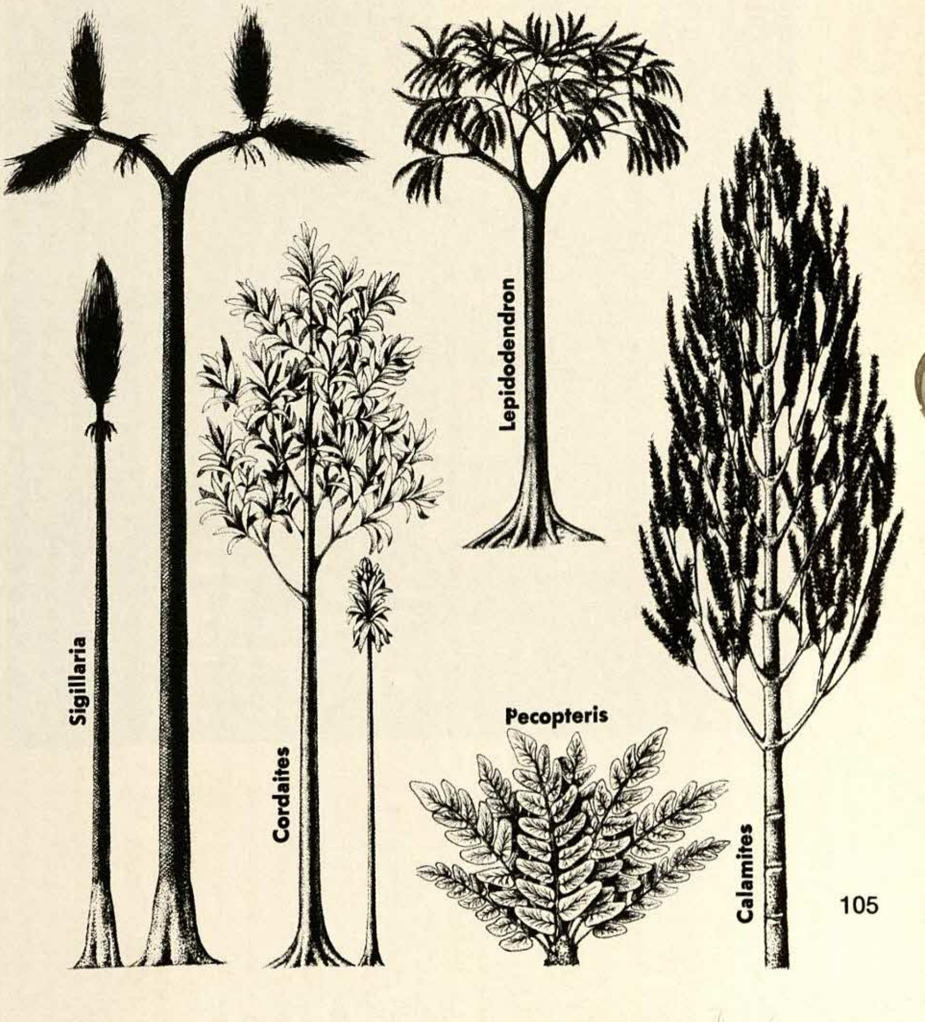
---

FLORA OF THE EURAMERICAN PROVINCE—The province within which this flora flourished was vast. The province included North America, where the flora was especially typical in the region now occupied by the United States; all of present-day eastern Europe up to the Don Basin, where Carboniferous coal deposits are found; and the coal regions of North Africa. To the east this flora was typical as far as Iran and modern Russian Turkestan.

The flora of this province is also called *Lepidodendron* flora, but other plants were typical of this province. Other widely diffused plants were *Calamites, Sigillaria, Pecopteris, Callipteris, Medullosa,* and *Cordaites.* In addition to these, pteropsids, gingkos, and conifers were also present.

These different types of plants have been grouped or classified according to the kind of environment in which they prevailed: dry, of average humidity, swampy, or lagoonal. For example, sphenopsids such as *Calamites* were prevalently found forming stalks or small trunks protruding from the waters of lagoons or deep swamps or near the edges of swamps; woods comprising lepidophytes were found around lagoons, because these plants thrived in damp areas and areas with water nearby. The Cordaitales forest, on the other hand, was typical of semiarid or arid regions.

The flora that has been described as being typical of a particular environment often alternates in coal deposits with flora characteristic of another environment. In coal deposits a *Calamites* may often be discovered in alternation with a *Lepidodendron.* This means that a lagoon slowly dried up and, as a consequence, one species of flora replaced the other. Later on, water covered the region, then slowly subsided, and a new succession began. During the Carboniferous, a continuous succession of transgressions and regressions of water facilitated the formation of highly abundant coal deposits. The climate of the Euramerican province must have been uniformly tropical due to the constant high temperatures and the lack of seasonal cycles, which interrupt the growth of plants for a certain length of time. These tropical conditions were conducive to the continual and massive production of vegetable material that eventually formed huge and extensive layers of coal.



cialization of associations occurred.

The history of the Carboniferous (which includes the Pennsylvanian and Mississippian periods) includes an initial period during which the plants invaded the continents more or less uniformly. Subsequently, different regions of the Earth became covered with forests that had different compositions of plant species, according to the climate and, in part, according to the evolutionary history typical of the region itself.

Later in the Carboniferous, evolution took place rather rapidly. Of course, this speed was quite relative, because evolution never progresses so rapidly in the Plant Kingdom as it does in the Animal Kingdom. In all, 60 million years were required to reach the degree of differentiation exhibited by the plants to be discussed here.

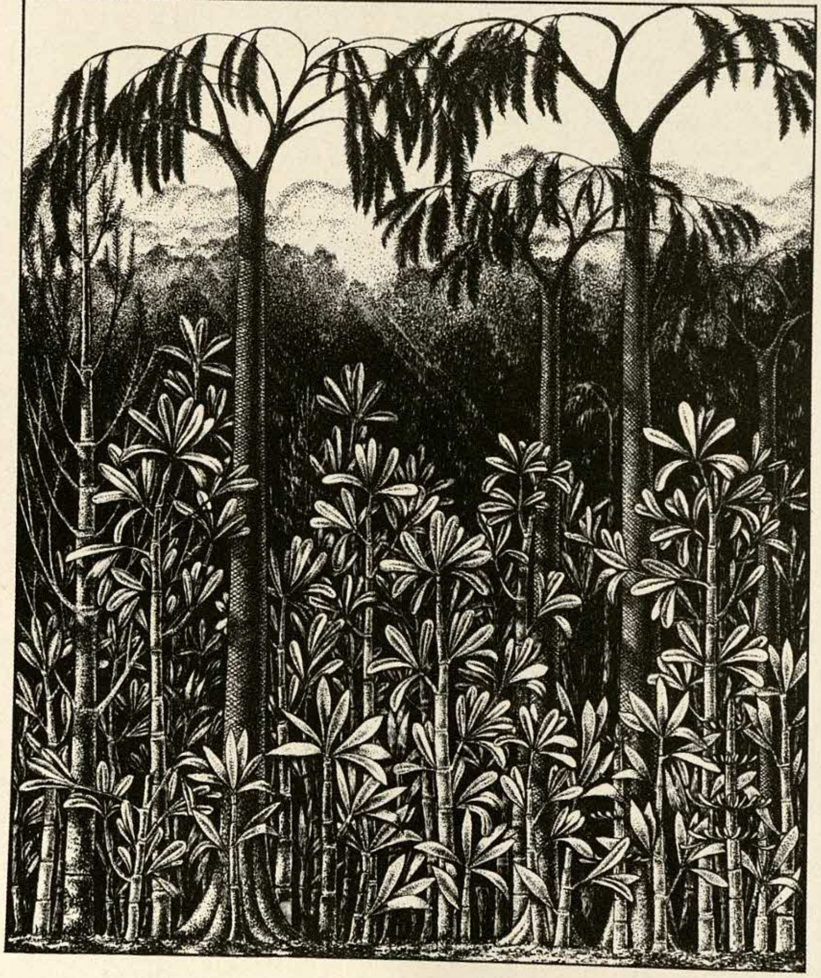
At first the composition of the flora was uniform over all the continents; afterward those species favored by the climate became dominant.

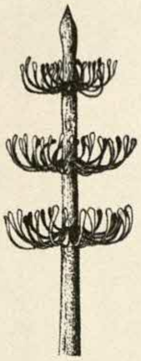
The first indication of plant evolution was the establishment of two great botanical provinces, one in the north (the boreal region) and one in the south (the austral region). This differentiation had already occurred in the beginning of the Carboniferous.

The boreal region included the lands of North America, Europe, and northern Asia. Almost all the vegetation characteristic of the Carboniferous was found

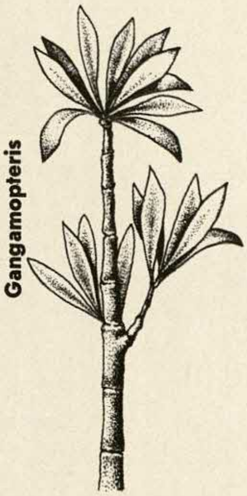
FLORA FROM THE PROVINCE OF GONDWANALAND—The fact that limited flora covered the austral zone during the Carboniferous has led scientists to hypothesize that the lands of the present-day southern continents were joined together as a single large continent called Gondwanaland. This hypothesis, in turn, supports Wegener's hypothesis concerning continental drift; the southern continents then either must have been separated from one another by small seas or they must have been adjacent to one another and connected by land bridges.

The area covered by the flora of Gondwanaland was typified by an aridity comparable to that of the Euroamerican zone; the composition of the flora, though, was characteristic of a lower mean temperature. The predominant plants in the forest of Gondwanaland were the *Glossopteris* and *Gangamopteris*, which, because of their abundance, give their names to the botanical province. Other typical plants were *Schizoneura*, and some other conifers such as *Buriadia* and *Walkomiella*.

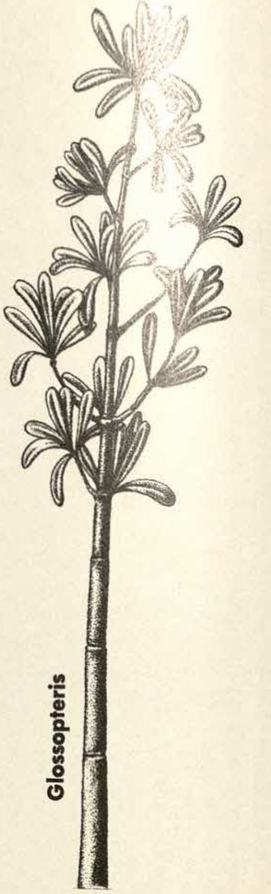




Neocalamites



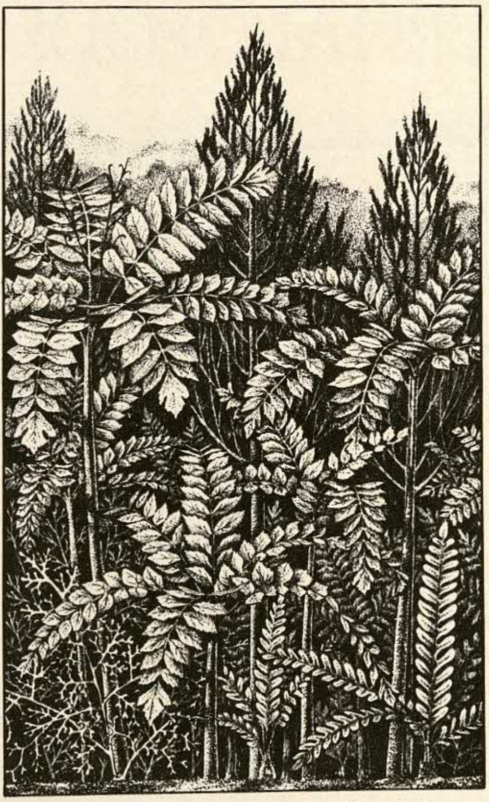
Gangamopteris



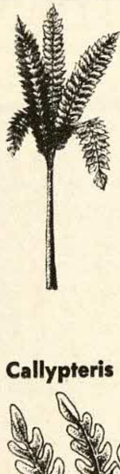
Glossopteris

Glossopteris

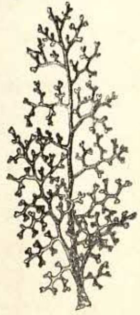
Gangamopteris



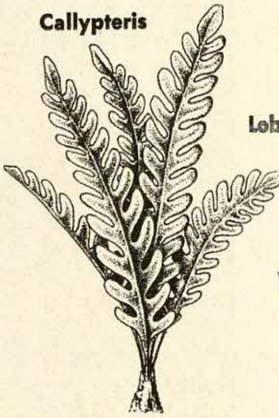
Gigantopteris



Sphenopteris



Callypteris



Lobatannulari

THE FLORA OF ANGARA—The province of the flora of Angara encompassed the Asiatic continent in correspondence with present-day northeastern Siberia. This region has always been separated from the rest of the Asiatic continent; often it was joined to the rest of Asia by a thin strip of dry land, which was sometimes situated to the north and sometimes to the south. This separation, together with the climate, brought about a characteristic flora, including *Sigillaria*, *Glossopteris*, *Gangamopteris*, and *Schizoneura*. Angara was noteworthy for an absence of conifers.

THE FLORA OF CATHAYSIA—The flora of this province developed in a region corresponding to the central part of modern China. The flora was found as far as Manchuria in the north and as far as Indochina and India in the south. The fact that the flora extended as far as Texas, Oklahoma, and Colorado means that the phenomenon of continental drift must have, in this case, worked in reverse, inasmuch as (according to the hypothesis), East Asia and America should have been separated by the largest of seas. However, this flora can be defined as that typical of warm and humid zones. The climate of southeastern Asia was, instead, similar to that of modern times. Lycopods and conifers were very rare or absent; *Lobatannularia*, *Chansiteca*, *Pecopteris*, *Sphenopteris*, *Callypteris*, *Gigantopteris*, and *Tingia* were abundant. The extensive coal deposits facilitated identification of the flora.

---

in this region; the forest flora was large and densely distributed.

The flora of the austral region, which included the so-called continent of Gondwanaland, was, on the other hand, much more uniform; the tree ferns of the genus *Glossopteris* predominated and formed forests that were sparser than those in the boreal region. The austral flora was less diversified, as only one plant species was dominant. In spite of the present-day location of the lands that formed the ancient continent of Gondwanaland, austral flora was typical of a cold climate, while that of the boreal hemisphere was characteristic of warm regions.

Toward the end of the Pennsylvanian period, the two botanical provinces were transformed into three provinces and eventually, during the Permian period, into four floristic regions. Normally, these provinces are named for the geographic regions in which they developed, but they may also be identified by the names of the predominant plant species.

The following are the four types of flora found on the Earth at the end of the Pennsylvanian period:

1. *Flora of the Euramerican Province*—also called *Lepidodendron* flora, after the largest and most widely diffused species.
2. *Flora of Angara or the Siberian Continent*—characterized by ferns of the *Glossopteris* genus.
3. *Flora of Cathaysia*—or *Gigantopteris* flora.
4. *Southern flora or flora of Gondwanaland*—also characterized by the *Glossopteris* ferns.

The existence of extensive coal deposits has facilitated the identification of the flora of this period. Sometimes, however, plants were better preserved in rocks that were consolidated from fine ooze; in such fossils it is possible to observe, even today, the more delicate structures, such as the leaves or the bark.

THE CEPHALOPODS | nautiloids and belemnites

Some 500 million years ago, when the Earth was populated by marine invertebrates only, certain groups of mollusks took the first steps of their evolutionary development. These groups have left fossil remains testifying to their existence. During the Cambrian period of the Lower Paleozoic these animals were already well developed. Therefore, they had their origins much further back in time. Very little is known about life in Precambrian times, because the rocks laid down in those times have since undergone changes that have obliterated most traces of organic material; consequently, the reconstruction of the evolution of plants and animals must begin, generally, with the onset of the Paleozoic era when fossilized remains first become abundant. Among the mollusks dating back to the early Paleozoic are the first gastropods, pelecypods, and cephalopods.

The cephalopods have played a role of great importance among the mollusks that populated the Earth during past geological eras. Even today they are quite abundant, and they were even more prevalent in the distant past. The great variety of different types is extremely useful to geologists today in establishing the chronological succession of sedimentary formations, especially those of the Mesozoic era.

The cephalopods are similar to the rest of the mollusks in general structure, but they appear to have the greatest affinity with the gastropods. Their visceral mass is more or less elongated and covered by a fleshy mantle. The latter, which may secrete a shell, encloses a cavity in which the gills are suspended. The alimentary canal contains the characteristic molluscan rasping tongue or radula. Cephalopods differ from the rest of the mollusks primarily in that the head and foot are in proximity (the mouth is situated in the middle of the foot) and in that the edges of the foot are drawn out into a number of fleshy appendages—arms and tentacles. The area immediately above the edge of the foot is formed into the funnel, an organ of locomotion. Most of the living cephalopods have fins, and their shell is internal and in a reduced condition. Many fossil cephalopods encumbered with a large external shell were poor swimmers, but most modern cephalopods are among the best adapted of all animals for an active life in the sea. The living *Nautilus*, however, retains the shell in a complete condition; and it is not a vigorous swimmer. For invertebrate animals, the cephalopods attain a large average size. The giant squids are actually the largest living invertebrates, the Atlantic species *Architeuthis princeps* attaining a total length of about 18.5 m (about 60 ft) with tentacles extended. Some squids and octopuses, however, are only 2.54 cm (1 in.) long. The shell of the fossil ammonite *Pachydiscus seppenradensis*, from Cretaceous rocks in Westphalia, Germany, measures about 2 m (almost 7 ft); it is believed to be the largest shelled mollusk. Cephalopods, one of the major groups of marine animals, prey upon crustaceans and small fishes principally. In turn, cephalopods are the prey of toothed whales and other marine carnivores. Whole squids often have been found in the stomachs of sperm whales.

The class Cephalopoda is divided into two great groups: the Tetrabranchia and the Dibranchia. The former include the Nautiloidea (in the broadest sense) and the Ammonoidea, while the latter include most of the cephalopods living today, as well as many similar extinct groups.

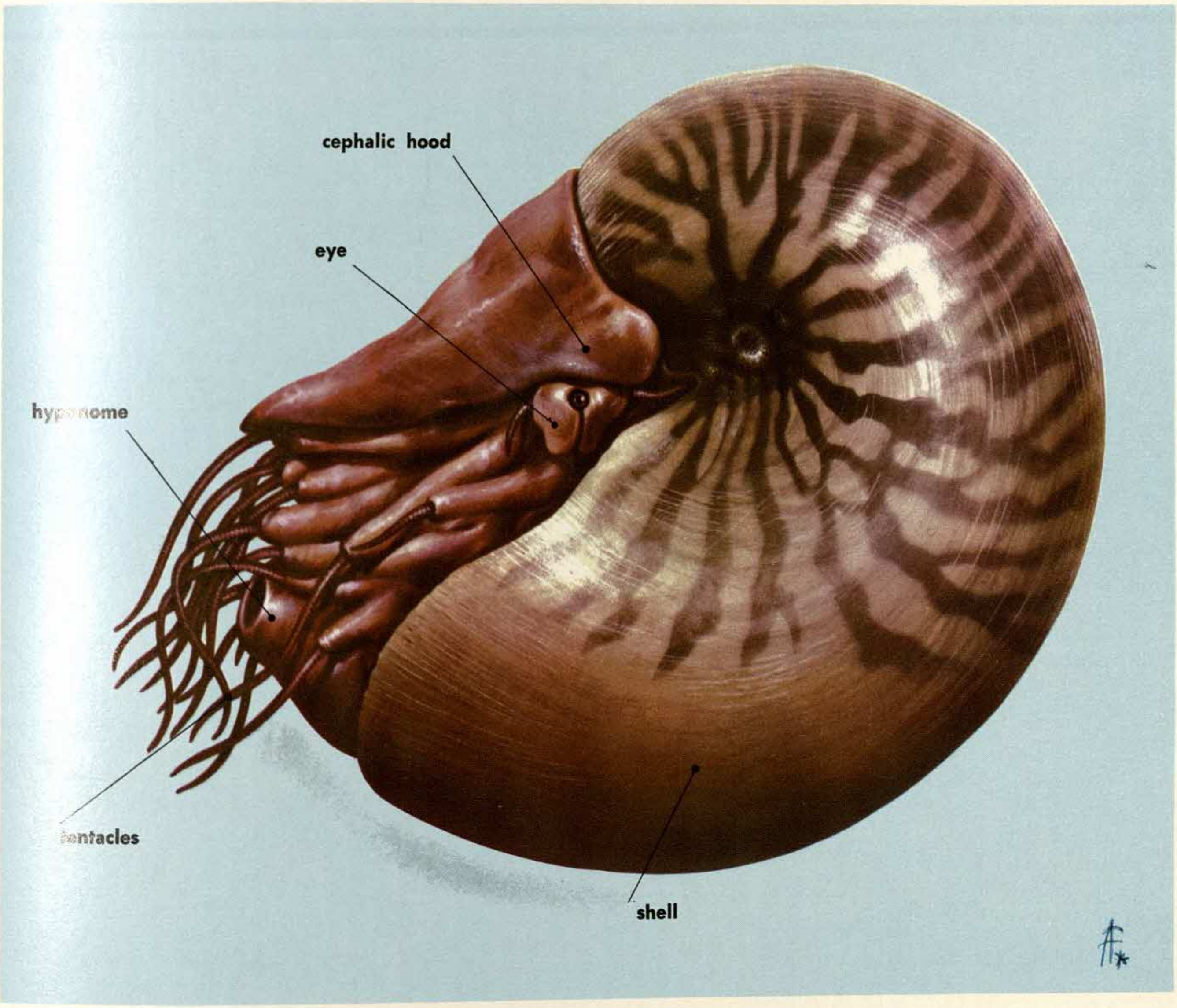
THE NAUTILOIDS

Among the cephalopods, the nautiloids represent the most ancient group from which both the ammonoids and the dibranchiates are derived phylogenetically. Furthermore, unlike certain other groups, the nautiloids have survived to the present day, although with very few representatives. In modern days, these representatives of an antiquity lost in distant time comprise five species of the *Nautilus* genus. It must not be thought, however, that the representatives of this extremely ancient group have remained unchanged in time, or that the species still living are the image of the first nautiloids. During the long period of their existence on Earth, the nautiloids have evolved enormously, with changes occurring in the form of the shell, in internal anatomy, and more importantly in behavioral patterns.

The first nautiloid representatives appearing during the Cambrian period were primitive types with straight or slightly curved shells, and they were not very abundant. During the whole of the Paleozoic era, an evolutionary explosion occurred which gave rise to a multiplicity of forms, but, at the same time, tended toward the development of planospiral winding of the shell. This process was completed by the beginning of the Silurian period, during which the nautiloids reached their apex, having passed through the intermediate stages of the arched shell, the coiled shell without sutures between successive turns, shells that did not overlap, and finally shells with turns that completely overlapped. The final results of this evolutionary tendency are apparent in the modern nautilus, in which the last turn completely covers the others.

With the end of the Paleozoic era a rapid regression began, probably as a result of competition from the more specialized ammonites, which began their evolution during this period.

In the Lower Jurassic period, just at a time when the ammonites reached the height of their development, the nautiloids virtually disappeared, leaving only one genus, *Nautilus*, which has survived to the present day.

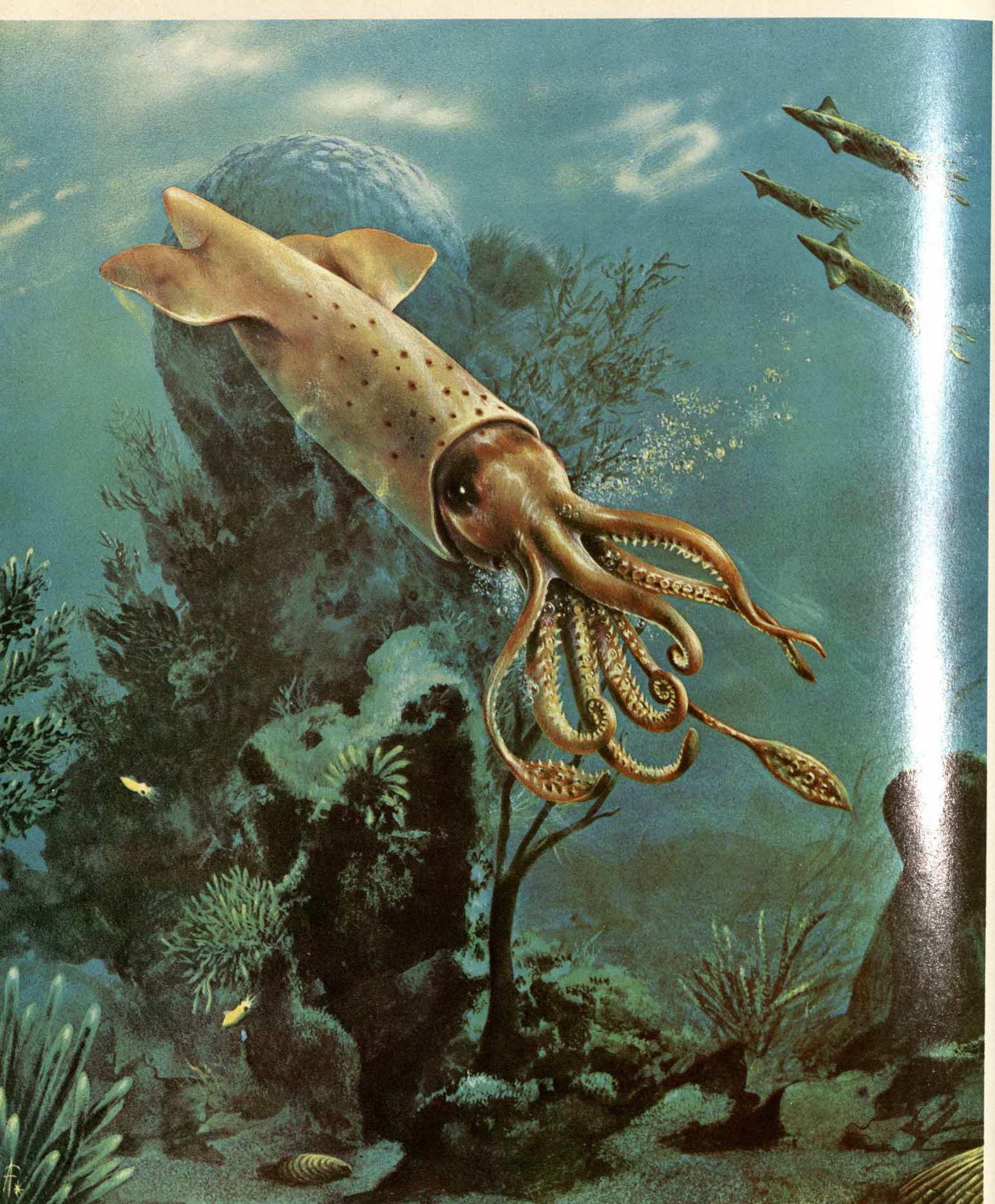


A MODERN NAUTILOID—Geologists know a great deal about the ecology of the living *Nautilus* shown here. They have used this knowledge to reconstruct the habits of this animal's direct ancestors (that is, the representatives of the Nautiloidea), which presumably had similar habits.

The present-day nautilus is localized exclusively in the southwestern part of the Pacific Ocean; this seems to indicate that its habitat is directly dependent on the temperature and salinity of the water. The nautilus lives at a depth of about 500 m (about 1,600 ft), but moves toward the surface every evening, in all probability following the migrations of plankton; in fact, the animal has been caught at a depth of only 20 m (about 65 ft). On the other hand, the nautilus apparently cannot live on the surface. It is an excellent swimmer, with quick movements caused by the rhythmic ejection of water from the branchial chambers through the hyponome.

The tentacles probably are used to furnish a solid anchorage on the rocky substratum for brief periods. Small quantities of shells of dead nautiluses have been carried by the currents as far as the coasts of Madagascar and Japan; nevertheless, postmortem transport probably is not very important today and probably was not important in the past.

Geologists, through their studies of living nautiluses, have been able to reconstruct a fairly clear picture of the ecology of nautiloids that lived long ago; ecological reconstructions for fossil groups that are totally extinct are much less clear, however.



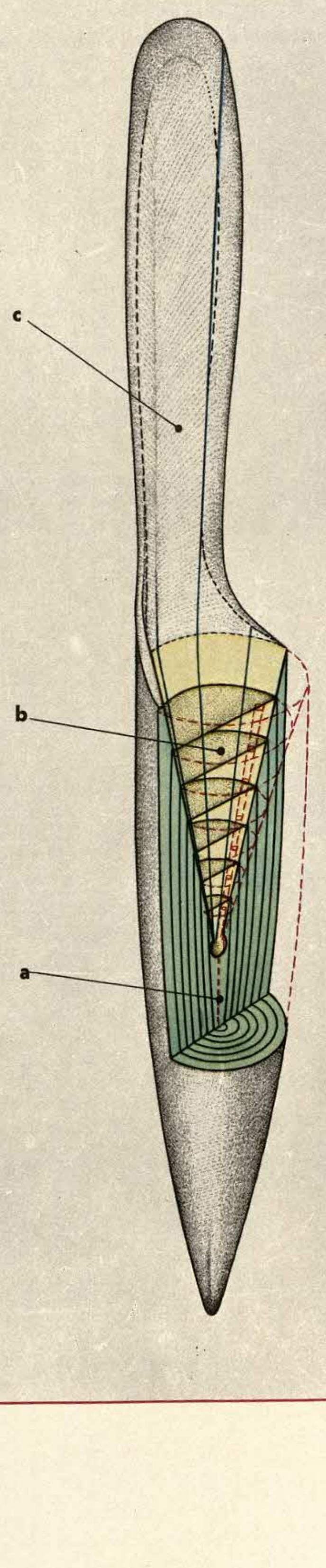
JURASSIC BELEMNITES IN THEIR NATURAL ENVIRONMENT—The belemnites, animals very similar to modern squids, were fast swimmers that moved backward by violently ejecting water from a hyponomic siphon located in the cephalic region; caudal fins served as stabilizers. The belemnites escaped from their enemies by emitting a black, inky fluid, and captured their prey through the use of tentacles.

THE DIBRANCHIATES

The order Dibranchia contains two families, the octopods and the decapods. The octopods include some rare fossil forms, the present-day octopus, and the argonaut or paper nautilus, with its very fine white external shell. The octopus appeared during the Upper Cretaceous, while the argonaut came on the scene during the Tertiary. The decapods, which are much more important from a paleontological point of view, include the present-day squids and cuttlefish and their ancestral relatives, the belemnites. The first squids appeared during the Tertiary; the older belemnites probably date back to the Upper Paleozoic, but the first certain representatives are found in Triassic formations.

All cephalopods have shells. In some groups, such as the nautiloids and ammonoids, the shell is external and has a protective function; in other groups, the shell is internal and serves (in a manner similar to that of a skeleton) to support the soft parts of the body. The famous "bones" of the cuttlefish and the well-known "pen" of the squid are actually very light internal shells. The shells of these modern dibranchiates are much smaller than those of their fossil representatives. The strange shell of the belemnite, therefore, can be related to these internal structures of the present-day decapods.

In Mesozoic rocks, especially those of the Jurassic and Cretaceous periods, paleontologists have discovered fossil remains that are cigar-shaped, very hard, and completely calcified. For nineteenth-century scientists, these fossils presented many problems; however, the discovery of the imprints of the anatomical parts of these animals finally enabled scientists to compare them with living cephalopods. It was established that most of these elongated remains were simply fragments of the internal shells of animals similar to the modern decapods. Paleontological reconstructions thus revealed animals, the belemnites, that were similar to the squid—although squatter, perhaps less highly developed, and often of considerable size. Indeed, the reconstructions brought to mind the ancient fables concerning monsters of the deep. Not all the "monsters" were so highly developed, however; the entire group, after having lived for about 130 million years, became extinct, along with other groups, for unknown reasons.



STRUCTURE OF THE BELEMNITE SHELL— The shell of the belemnite was internal. It was divided into three principal parts: the rostrum, or guard **a**, the phragmocone **b**, and the proostracum **c**. Because the rostrum was the most solid and resistant part, it was the most commonly preserved; it was, in fact, completely filled with calcite in the form of small prisms arranged radially around the axis. The shell had a more or less elongated shape, similar to a cigar, but in some species it was considerably flattened. Furthermore, the ratio between its length and its diameter varied considerably, so that the forms ranged from squat to elongated. Variations also existed in the shape of the apex: in some cases, it ended in a sharp point; in others, it was rounded off; and in still others, it presented a protuberance called the mucro. The rostrum often bore ornamentation that varied with the species. The ornamentation was formed by granulation and furrows on the dorsal and ventral parts. Geologists use the ornamentation to classify species, because it is believed to consist of traces of muscular insertions and, therefore, probably is related to the soft parts of the animal's body. The upper portion of the rostrum presents a conic depression (alveolum) into which the phragmocone fits.

The phragmocone was the most important part of the whole shell, but because of its extreme fragility, it has rarely been preserved in the fossil state. Basically it consisted of a conic portion that was perpendicularly divided by circular septa. The septa normally were crossed by a siphon located in a ventral position. The phragmocone, because of the presence of the septa and the siphon, corresponds exactly with the septated part of *Nautilus* and seems to have had the function of a floating organ. By means of the siphon, it permitted variations in the specific weight of the shell, thus allowing the animal to move up and down. In the better-preserved specimens the external conic wall (conotheca) is visible; on this wall the septa have left characteristic insertion lines, similar to the suture lines of the ammonites.

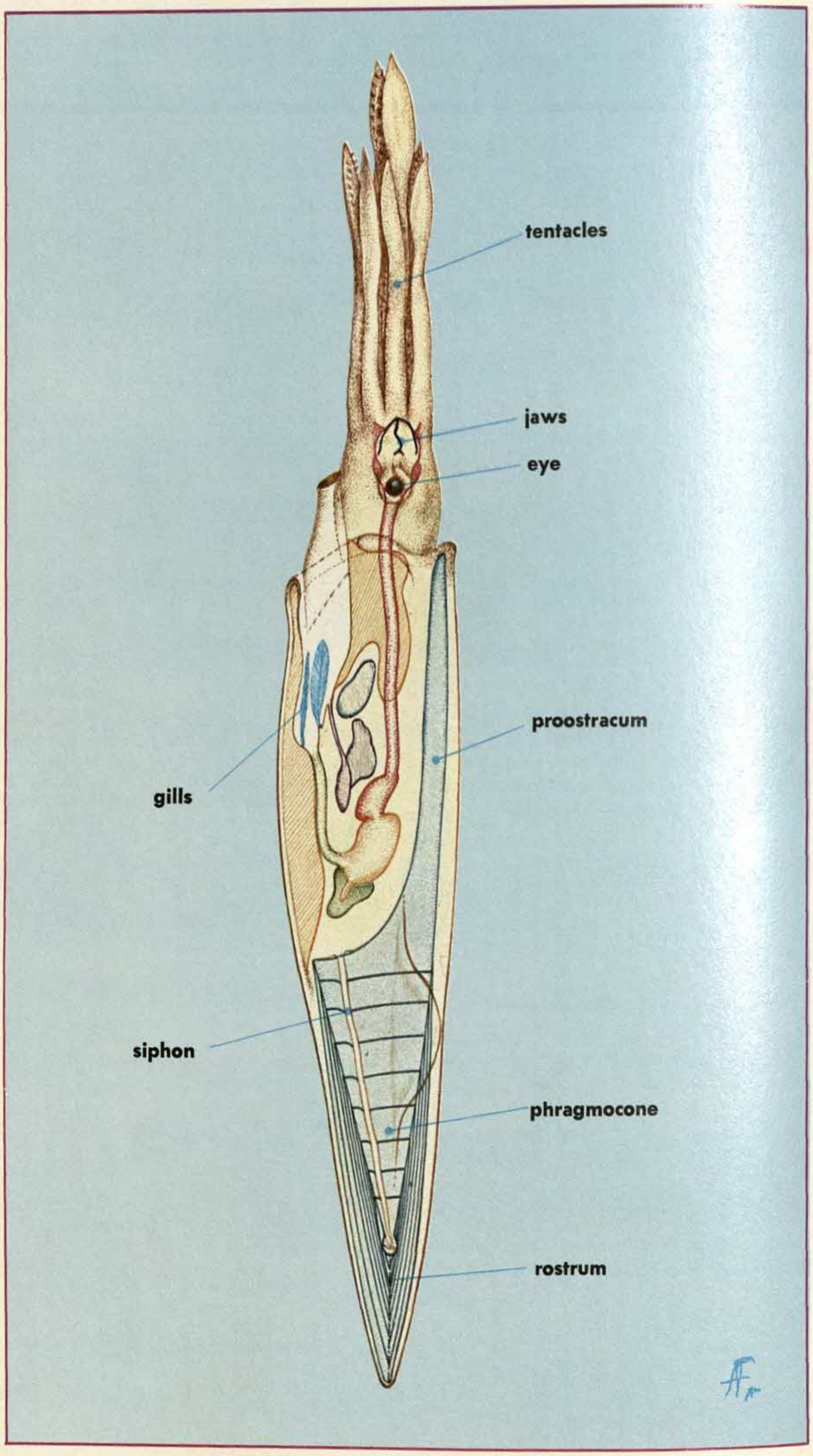
The conotheca extended dorsally into a very delicate, elongated structure, the proostracum. The latter has rarely been preserved, not only because of its extreme fragility, but also because it was composed of a horny substance impregnated with aragonite. The proof of the internal position of this structure has been furnished by the absolute lack of a living chamber and by the presence of the aforementioned imprints on the external walls of the rostrum.

RECONSTRUCTION OF THE SOFT BODY OF A BELEMNITE—In reconstructing the forms of ammonites, geologists have had only the shells to work with. However, in the case of the belemnites, geologists have discovered extremely rare imprints of the outer part of the belemnite body, fossilized in the fine limestone deposits of Solnhofen and Molzmaden in Germany and Lyme Regis in England. These imprints were left by the dead animals as they sank onto the very fine layer of silt that covered the bottom of tranquil marine basins. Scientists have been able to observe in the imprints the presence of ink sacs (similar to those possessed by modern squids and cuttlefish) and of numerous tentacles located in the cephalic region around the mouth aperture, which is provided with tiny jaws. In some imprints eight tentacles are visible, while in others only six may be seen; nonetheless, all the tentacles are quite similar to those of living cephalopods.

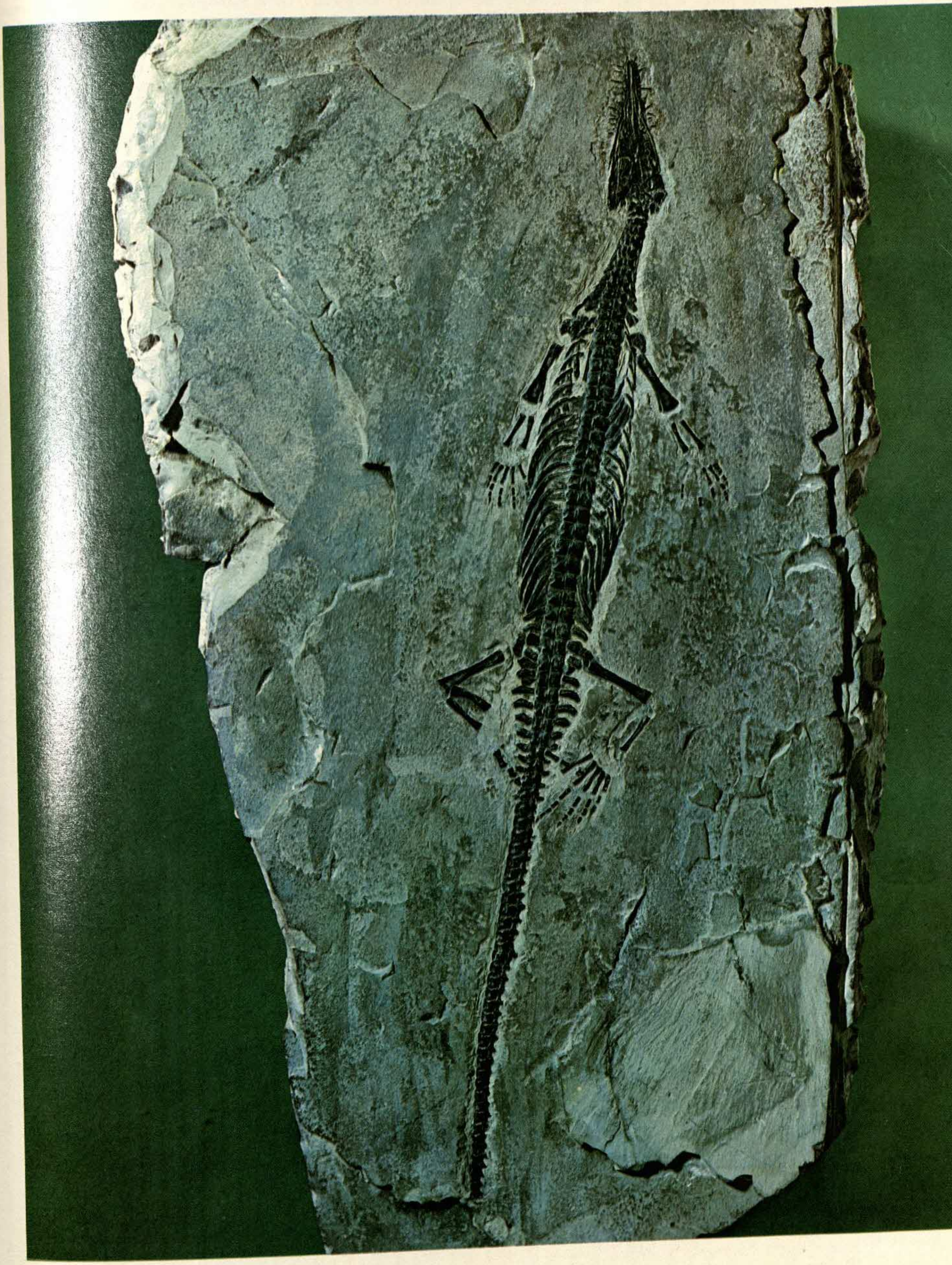
Basing their findings on these very rare imprints, discovered with the shell in situ, geologists have attributed these enigmatic fossils to the group of cephalopods and have carried out the reconstruction shown here.

The belemnites, therefore, appeared very similar to present-day squids and probably had the same living habits. They lived in a surface or coastal habitat and their larvae, because of the geographic extension, probably were planktonic. The different shapes of the shells undoubtedly resulted from adaptation to different ways of life.

Carnivorous and predatory, the belemnites were in their turn easy prey for the huge sharks of ancient waters. In fact, a fossil selachian with some 250 belemnite rostra in its stomach has been discovered. Apparently the belemnites normally lived together in large groups as do present-day cuttlefish and squids. This conclusion has been confirmed by the discovery of various fossil groupings.



THE PERMIAN PERIOD | the Earth at the close of the Paleozoic



← **A MESOSAUR FROM PARANA**—This fossil (Illustration 1) was discovered in Brazil, in the state of Paraná. The imprint of the skeleton of *Mesosaurus braziliensis* is well-preserved. This reptile, from the Permian period, is the first freshwater reptile known.

The Permian period, which marked the close of the Paleozoic era, was a time of momentous change. The Appalachian geosyncline, which had persisted for as long as 300 million years, was uplifted and folded into great mountain ranges, and changes in the life on Earth took place to give a hint of things to come. Other mountain chains were built up across central Europe and southern Asia and extended as far as the East Indian arc. At the same time a major movement of the Earth's crust in Russia created the Ural Mountains. Beginning in the middle part of Permian time volcanic eruptions in central Mexico, eastern California and Oregon, in Alaska, in southern Europe, and in Asia marked the beginning of the great igneous activity of the Mesozoic era. The close of the era was marked by a general uplift of all the continents of the Earth.

Seldom in geologic history has one period included the great diversity of climates that prevailed during the Permian. The great crustal movements that resulted in the uplift of the continents and the building of vast mountain ranges created barriers that disrupted the movement of air currents and restricted the distribution of heat and moisture. The rather uniformly warm temperatures that had persisted throughout much of the Paleozoic gave way to much cooler and drier climates in many areas.

A few localities, particularly in Asia and Australia, continued to have a warm, humid climate that allowed coal swamps to develop. Elsewhere, however, desert conditions probably were more widespread than during any other time in geologic history, except perhaps the present. In the central and western United States Permian deposits consisted of dune sands and red beds that covered wide areas; beds of salt, gypsum, and potash that probably were formed by the evaporation of many cubic miles of seawater record the sites of land-locked basins. In places these beds of evaporites attain a thickness of more than 300 m (about 1,000 ft). Other thick deposits of salt and potash of Permian age occur in the vicinity of Stassfurt, Germany, and west of the Ural Mountains in Russia.

Perhaps the most striking of all the varieties of Permian climates was the great glaciation in the Southern Hemisphere. South Africa has the most widespread evidence of Permian glaciation, but glacial deposits known as tillites also have been found in Australia, Brazil and Argentina, India and Russia. Less well-defined evidence also has been found in England, Germany and the northeastern United States. In Africa the movement of ice from three or four centers can be traced by large, faceted boulders, heavily scratched and polished bedrock floor, and tillite for distances as great as 1,100 km (about 700 mi).

What seems most astonishing about the Permian glaciation is that it occurred so near the equator. The Brazilian glaciation was within 10° of the equator and some Indian deposits have been found within 20° of the equator. Equally strange is the fact that the ice appears to have moved away from the equator.

The extensive glaciation in the Southern Hemisphere in addition to other evidence, mainly biologic, has suggested to some geologists that land connections existed between South America, Africa, India, Australia, and Antarctica during the Paleozoic and into the Mesozoic. These connections are believed to have been narrow strips of land, such as mountain chains, known as land bridges. Other geologists believe that the present continents may have been part of one vast continent to which the name Gondwanaland has been given.

As might be expected from the profound changes in climatic conditions, the Permian was a time of extraordinary change for life on Earth. An abundance of fossils of many different forms indicates that life as a whole flourished during the period. It was, however, a time of rapid evolution and great specialization for many groups of organisms, both plant and animal. One important result of these changes was the final disappearance of many of the groups that had persisted throughout the Paleozoic. Such

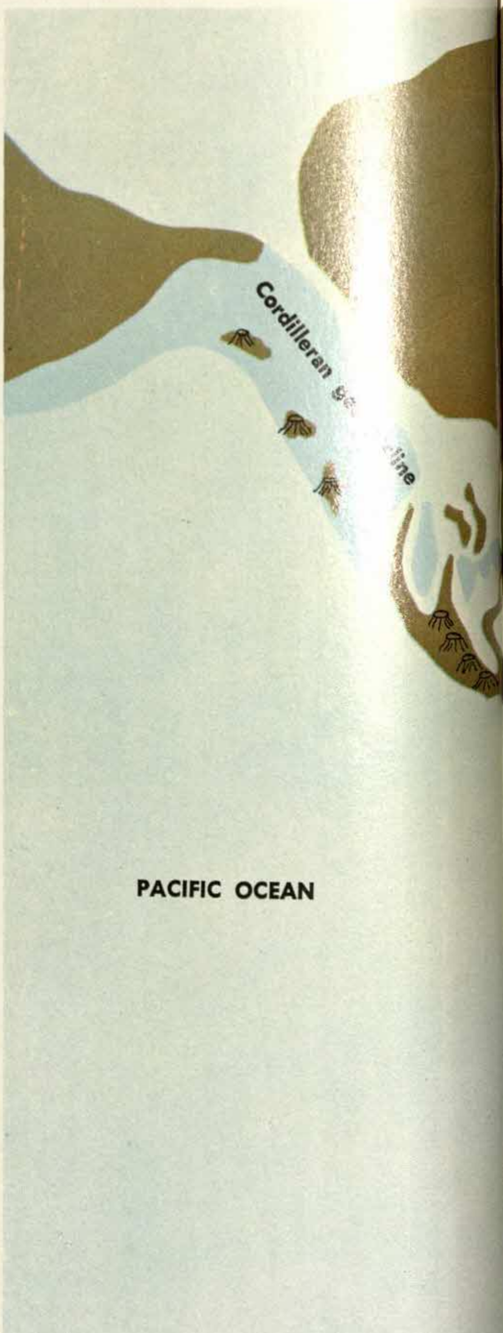
2

MAP OF THE PERMIAN WORLD—The geological changes that have taken place even in recent times sometimes are difficult to untangle; those that took place about 200 million years ago must seem virtually impossible to recognize. The work of many geologists, however, has provided clues to the past that fit together somewhat like a three-dimensional puzzle.

A picture of what some of these scientists believe to have been the relationship of the landmasses and the seas during Permian time is shown on this generalized planisphere. Because the continents then, as now, were emergent, their shapes and relative positions have a familiar appearance. Seas invaded the Cordilleran geosyncline in western North America during the Permian period, but the sediments deposited in western Europe, Russia, China, Argentina, Brazil, South Africa, and elsewhere were largely of continental types.

The map also shows areas in which volcanoes were active during the period. One zone was centered in Siberia, while another stretched along the western edge of Europe. In western North America volcanic rocks thousands of feet in thickness include a few thin marine beds that contain Permian fossils.

The extent of Permian glaciation also is indicated on the map. Evidence of early Permian glaciers has been found in parts of South America, Africa, Australia, Siberia, and elsewhere. It is probable that the Permian Ice Age occupied a relatively brief time in a long geologic period, but its wide distribution and probable effect on the life of that time make it worthy of note.



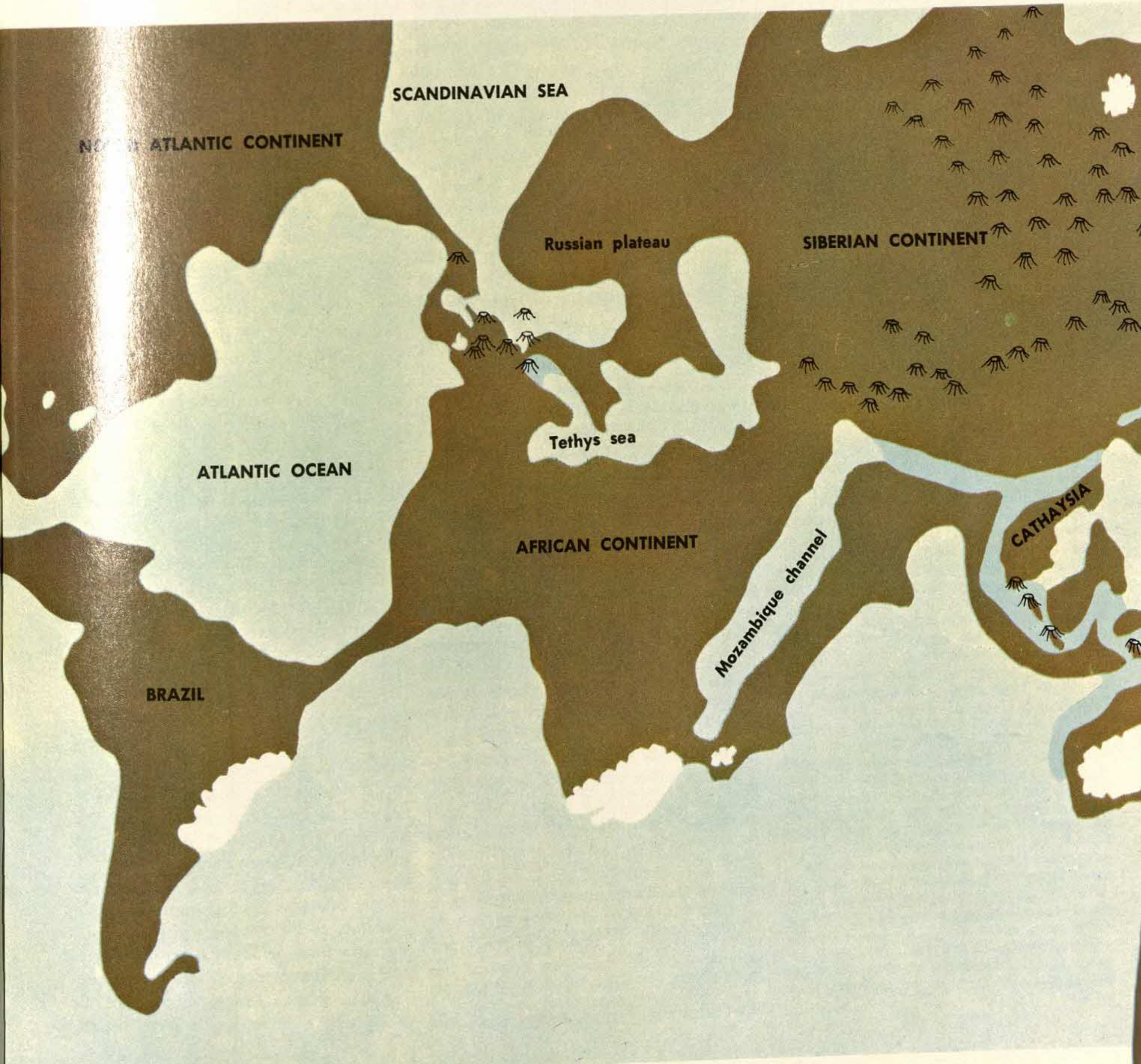
was the fate of the trilobites, fusulinids, tetracorals, and many other groups of invertebrates. Permian insects generally were not so large as some of those that lived during the Pennsylvanian, but they were numerous and displayed great diversification. One small locality in Kansas has yielded more than 10,000 specimens from a single thin bed in the Lower Permian.

Many of the important types of Pennsylvanian plants lived on into Permian time. Swamp-dwelling plants such as the lepidodendrons, seed ferns, sigillarids, and *Cordaites* were common during the early part of the period, particularly in Australia and Siberia. As the climate changed, however, plants that were poorly adapted to arid and cool conditions gave way to the conifers, cycadeoids and ginkgos.

Throughout the Southern Hemisphere and in parts of India, the glossopterises (tongue ferns) characterized the Permian floras. These small, hardy, seed-bearing plants were not ferns, but relatives of the cycads. Their wide distribution on the continents of the Southern Hemisphere and their absence in North America and Europe is cited as evidence for the Gondwanaland concept.

Among the higher forms of life the broad-headed, thick-bodied stegocephalians sprawled on the ground along watercourses, even in the semiarid regions. Reptiles increased greatly in variety during the Permian; some, such as *Varanops,* were similar in appearance to lizards, while others were thick-bodied and had short, thick legs. The most unusual of all were those of the "fin-back" group that included *Dimetrodon* and *Edaphosaurus.* These reptiles had long, skin-covered spines that extended upward from the vertebral column. This unusual extension made the animals appear to have sails on their back.

A group of heavily built reptiles with their legs set so that they carried their bodies off the ground had great significance for the future of the Animal Kingdom, however. Unlike other reptiles of that time, these animals, known as theriodonts, had teeth differentiated into incisors, canines, and molars. These characteristics and certain details of structure of the skull and jaw confirm their ancestral relationship to the mammals, which did not appear until the Mesozoic.



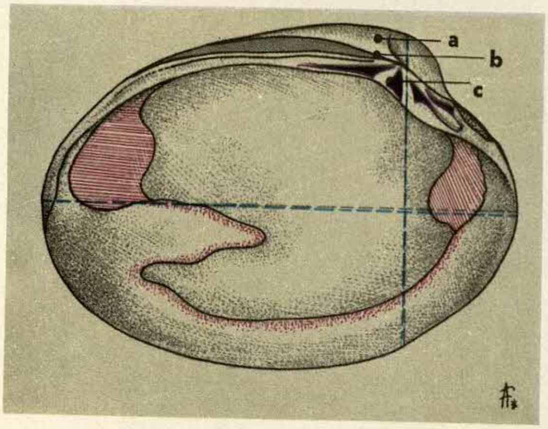
THE PELECYPODS | bivalved aquatic mollusks

The pelecypods constitute one of the most important and interesting groups of mollusks, both because of their great chronological importance and because of the various adaptations that the numerous species have made to different environmental conditions. Pelecypods are still very widely distributed both in the waters of the seas and in continental fresh waters. Clams, oysters, scallops, and mussels are some commonly known pelecypods.

The adaptability of these mollusks to diverse environments and their important place in the animal world of today make them a valuable aid to the paleontologist—on the one hand, for the comprehension of the fossil representatives of the group; on the other, for a better reconstruction of their lives and their habits during different geological periods.

The name *lamellibranch* is sometimes used in place of *pelecypod* and is derived from the peculiar lamellar (bladelike) structure of the gills, which are the respiratory organs of these mollusks. However, the terms *bivalve* and *pelecypod* are commonly used; the former derives from the fact that the outside shell is divided into two equal valves; the latter derives from the fact that the ventral foot is shaped like a hatchet. Pelecypods are characterized, above all, by an outer shell consisting of two valves hinged along the upper edge by means of a cardinal apparatus that permits reciprocal movements. These movements are controlled by two muscles inserted into the front and back walls of the inner shell. On the inside of the shell, whose function is purely protective, is the soft part of the animal; this part has never been found in fossil form. The soft part consists essentially of a mantle that lines the inside of the two valves and envelops the visceral sac, leaving two openings, one at the back and the other at the front, where the gills carry out their function of absorbing oxygen from the water. The water is made to circulate by a system of tubular siphons, but the latter are sometimes replaced by simple openings.

1



NOMENCLATURE OF A GENERALIZED PELECYPOD SHELL—The principal characteristic of the pelecypod shell is the presence of two equal valves; these, however, because of adaptation to particular environments, may vary greatly in size and other characteristics that serve to differentiate them. The scallop (*Pecten*), for example, is a small mobile form in which one valve has an opercular or lidlike appearance; other forms (*Ostrea, Rudista*), which have elongated shells that can take on the shape of a cone, are attached to the bottom.

On the outside, the top portion of a pelecypod shell curves, generally toward the front of the shell, called the umbo **a;** the back part of the shell is therefore larger than the front. Under the umbo, along the top part, is the ligament **b** that holds the two valves together and permits their reciprocal movement; farther down is the hinge **c,** a structure that, on each valve, consists of parts that protrude (teeth) and fit into sockets (fossettes) in the opposite valve. This complex structure makes it possible for the valves to open and close without lateral movement.

Some pelecypods are able to anchor themselves to a solid substratum through the secretion of a substance known as filaments of byssus.

The foot, an organ of locomotion, is practically an extension of the visceral sac toward the bottom; when the mantle is ventrally closed, the foot protrudes through an opening in the mantle.

The zoological classification of the pelecypod is based essentially on the aforementioned organs, without any reference to the outer features of the shell. For the paleontologist, on the other hand, the task is more difficult; his classification, which is based on the shell only, turns out to be completely different. He uses those features of the shell that reflect the main outlines of the structure of the animal's body. Among these features, for example, are the imprints left by the muscles on the insides of the shell at their insertion points; these imprints enable the paleontologist to establish whether the animal possessed a single muscle (in which case it is known as a monomyarian pelecypod) or two muscles (in which case it is known as a dimyarian pelecypod). Moreover, if the animal was a dimyarian, the imprints enable the paleontologist to determine whether the two muscles are equal (isomyarian) or different (heteromyarian). Another indicative feature is the insertion line left on the lower edge of the shell by the muscles that surround the edge of the mantle (pallial line); this may present in the back a wide enlargement (sinus) that corresponds with the passageway of the siphonal apparatus, when present, thus making it possible to establish whether the pelecypod is siphonate or asiphonate.

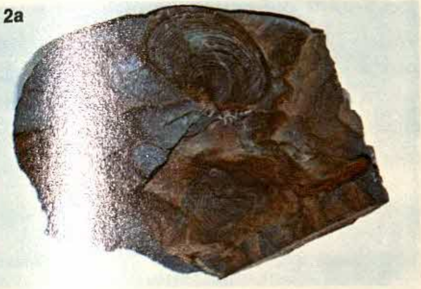
The paleontological classification is nevertheless based principally on the cardinal apparatus, which exists in many widely varying forms. These forms seem to have appeared in several stages in more or less direct reciprocal derivation; they are, therefore, extremely useful inasmuch as they provide the data necessary for tracing the approximate main lines of pelecypod evolution.

THE SCIENTIFIC IMPORTANCE OF PELECYPODS

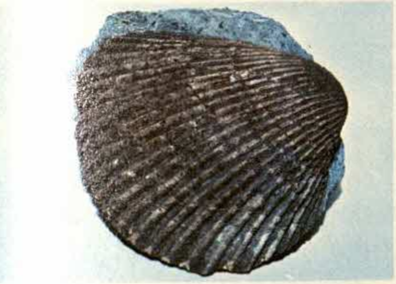
According to the actualistic theory, natural phenomena occurred in the past in the same way as they take place today. Therefore, paleontologists, by studying the fossils contained in a rock and comparing them with living representatives, are able to deduce the characteristics of the environment in which the fossils and rock were deposited. This interesting branch of the Earth sciences is called paleoecology. Paleoecological studies, in many instances, have enabled scientists to reconstruct the appearance of the Earth in past geological periods and to follow its evolution progressively. Clearly, therefore, the pelecypods are very useful in this type of research because their wide distribution in present-day waters facilitates the comparison of live specimens and fossils. The enormous capacity of the pelecypods to adapt to various natural environments is so refined that it has provided numerous species, each of which is bound to a particular and well-determined way of life.

Natural environments may be classified into three large groups: marine (oceans), continental (fresh waters), and transitional (lagoons and deltas). Each of these groups may be further subdivided on the basis of different chemical and physical properties—such as salinity, temperature, depth of water, and, therefore, pressure—that limit the migration of species from one environment to another. For example, suppose that scientists discover the fossil remains of the *Cardium* or *Venus* genus of pelecypods. Because these organisms are known to live in shallow water off sandy or muddy beaches, scientists may assume that the place where these fossils were discov-

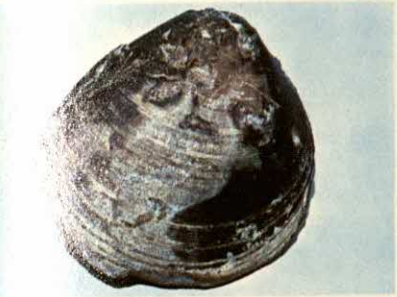
2a



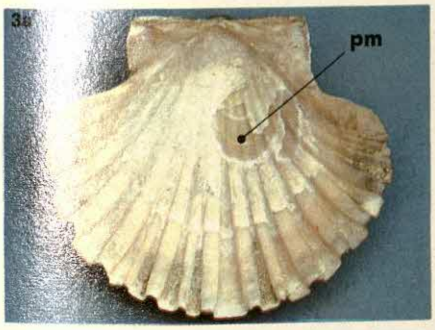
2b



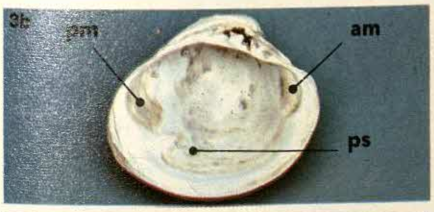
2c



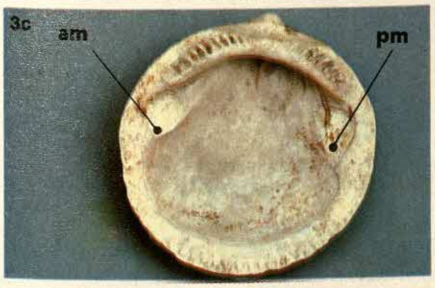
3a



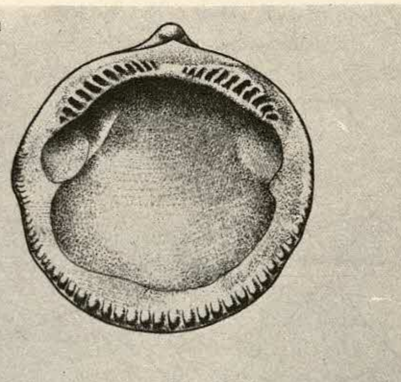
3b



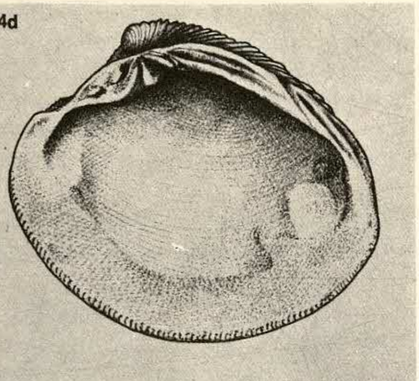
3c



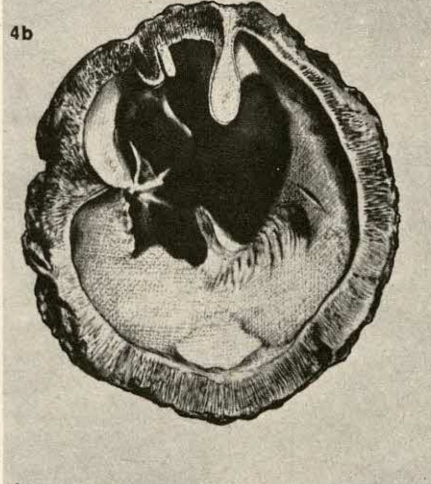
4a



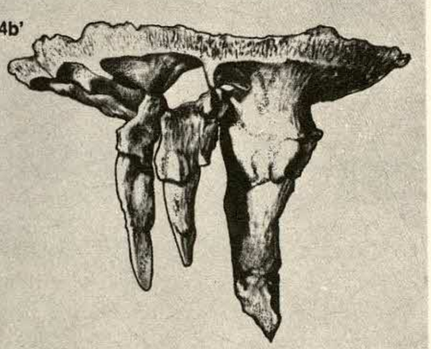
4d



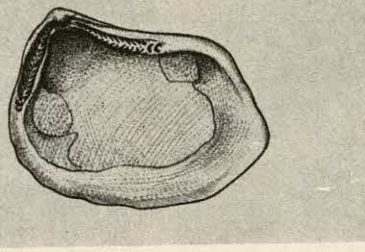
4b



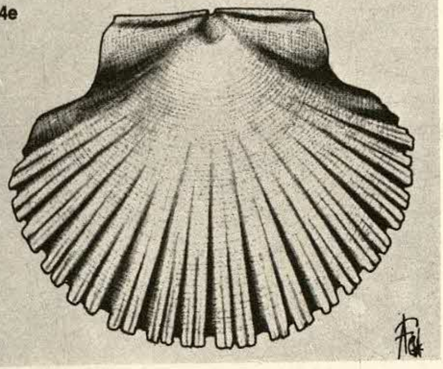
4b'



4c



4e



ORNAMENTATION OF THE SHELL—These illustrations provide examples of the external appearance of pelecypod shells. In general, two different types of ornamentation are found: one type (Illustration 2a) is concentric with respect to the umbo (concentric sculpture); the other type (Illustration 2b) radiates outward from the umbo (rayed sculpture). The ornaments, for the most part, consist of cords, ribs, striations, and laminations, over which spines or other more complex structures are superimposed. The two types of ornamentation may be present on the same shell, giving rise to a network pattern. Furthermore, during the development of the shell, phases of rapid growth alternate with static periods, thereby leaving growth marks or striations on the outer surface—marks that are clearly distinguishable from the variety of ornamentation (Illustration 2c).

INNER SURFACES OF THE VALVES—These photographs show examples of shells with the imprints left by the soft parts on the internal walls of the valves. Illustration 3a shows an example of a myarian pelecypod (*Pecten*) with a posterior muscle only **pm.** Illustration 3b depicts a dimyarian lamellibranch (*Venus*) with anterior muscles **am** and posterior muscles **pm** of equal development and with a pallial sinus **ps.** Illustration 3c is an example of a dimyarian pelecypod (*Glycimeris*) with muscles at the front and back, but without a pallial sinus.

CLASSIFICATION OF THE PELECYPODS—Very few features are considered in the paleontological classification of pelecypods. The principal features are the muscular imprints and the hinge, as they are related to internal structures that do not undergo variations of any great importance in the various adaptations. In fact, the first subdivision of the class into orders is based on the hinge. The following list enumerates orders and describes the most important characteristics of the cardinal apparatus.

Taxodonta (Illustration 4a)—This order comprises bivalves with a taxodont hinge, formed by an ample cardinal area bearing a large number of small and regular teeth separated by sockets. The teeth on each valve correspond to the sockets on the opposite valve.

Pachyodonta (Illustrations 4b and 4b')—This order, which includes the extinct *Rudista,* is characterized by a pachyodont hinge with teeth that are few in number but large and deformed.

Preheterodonta (Illustration 4c)—Members of this order are equipped with a schizodont hinge with a small [illegible]umber of strong, grooved cardinal teeth. In t[illegible] left-[illegible]and valve, a single tooth separates tw[illegible] soc[illegible]ets, while the two teeth in the right-ha[illegible] va[illegible]e are separated by a single socket.

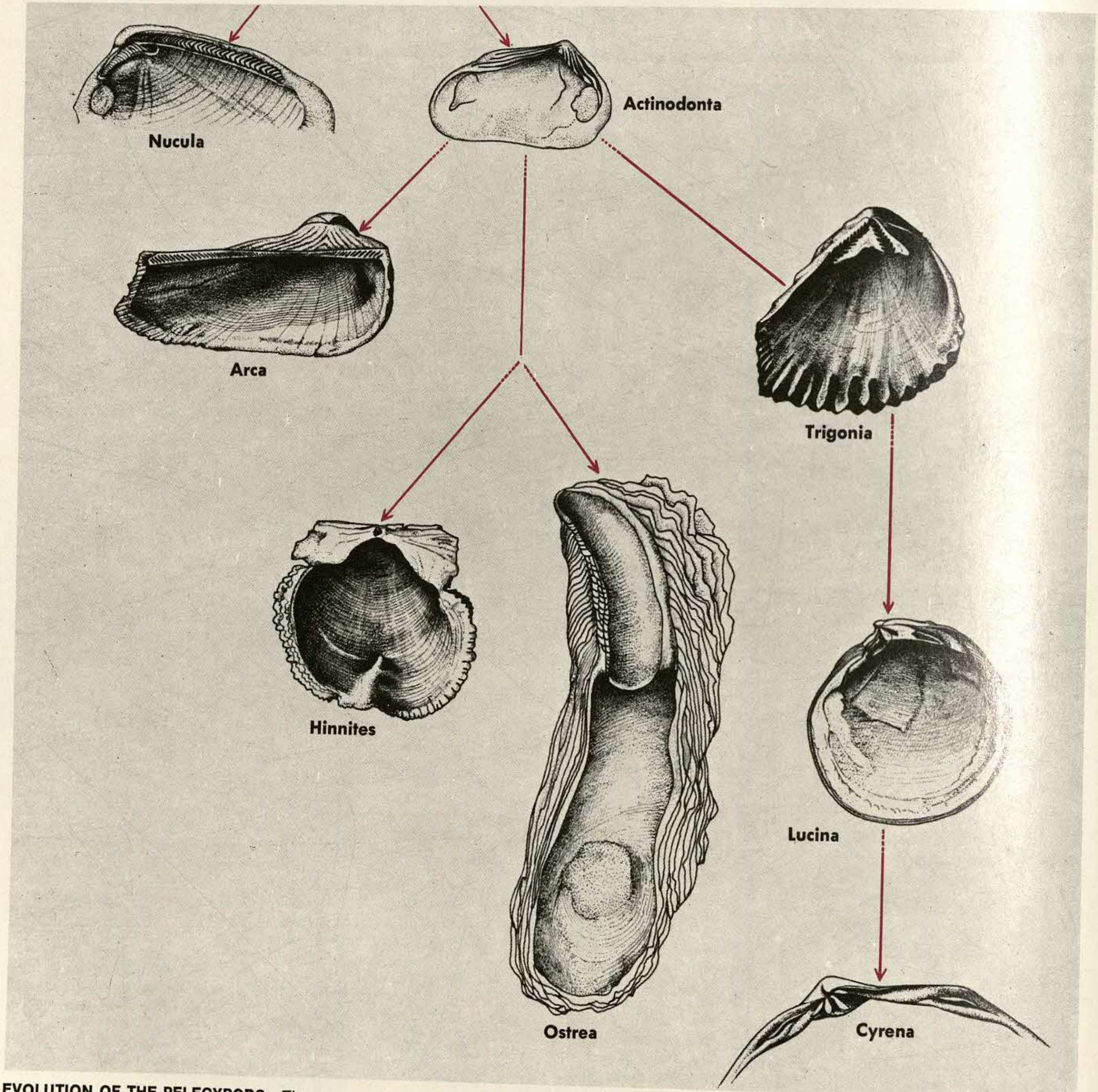
Heterodonta (Illus[illegible]tion [illegible]d)—Pelecypods of this order have a h[illegible]od[illegible] hinge with teeth differentiated from [illegible] [illegible]in[illegible] perpendicular to the cardinal borde[illegible] [illegible] [illegible]le ones that are parallel to the bor[illegible]

Dysodonta (Illust[illegible] 4[illegible] Members of this order are characte[illegible] [illegible]ysodont hinge; teeth may be few i[illegible] [illegible]associated, or totally absent.

ered was once a shoreline with a shallow sea and a muddy or sandy bottom. Suppose, however, that the scientists had discovered remains of the *Cingeria* genus; then they could conclude that the site had been an ancient lagoon with a slimy bottom and a low salt content.

In conclusion, the pelecypods are of scientific importance because they offer a good selection of index fossils, which are highly useful in determining geological chronology. More significantly, the location of pelecypod fossils enables scientists to reconstruct the geographic face of the continents during various geologic periods and to trace the changes that have occurred in different places on the Earth through the ages.

5



EVOLUTION OF THE PELECYPODS—The earliest known pelecypod specimens date from the Cambrian period, that is, over 500 million years ago. Scientists believe that they were derived from primitive forms with a mother-of-pearl shell like that of *Nucula*, a genus still living today. From those first rare forms, new groups evolved incessantly during the Silurian and subsequent periods; some of the new groups became extinct after a certain period of existence, while others have survived almost without change to the present day. The evolutionary history of the pelecypods seems to be very difficult to reconstruct. One hypothesis—among the many that have been proposed—is based on the transformations of the hinge that took place in the course of geological time. It seems that pelecypods with primitive taxodont hinges (*Actinodonta*) developed into three distinct evolutionary lines. The first of these lines led to the pseudoctenodont type (*Arca*) by means of the progressive curvature of the teeth; the second, through the loss of the teeth, to the dysodont type (*Ostrea, Hinnites*). The third and most important line initially gave rise to forms with schizodont hinges (*Trigonia*), from which were derived the heterodont lucinoid types (*Lucina*) and subsequently, through the shifting of teeth, the cyrenoids (*Cyrena*). Finally, in order to adapt to an environment different from that of the rocks, the pelecypod evolved the form of *Rudista* with a pachyodont hinge (*Diceras*).

PERMIAN FAUNA | animal life at the end of the Paleozoic

The Paleozoic era began about 550 to 570 million years ago and witnessed the first great development of plant and animal life on the Earth; at least, Paleozoic rocks are the earliest to yield fossilized remains of large numbers of primitive organisms. This great and long era came to a close with the end of the Permian period some 325 to 345 million years after it had begun.

The Permian derived its name from the Perm district in the Ural Mountains, where rocks from this period were first recognized and studied. The period began about 260 million years ago and lasted about 35 million years—or until about 225 million years ago. From the point of view of fauna, the Permian constituted a transitional stage between the oldest and most primitive Paleozoic organisms and those of the Mesozoic era, which tended toward a generalized modernization of structures.

Among the many living organisms that populated the lands and seas during the final period of the Paleozoic era, not many can be linked to living genera and species. A span of approximately 260 million years is too long a period for even the hardiest species to survive without mutation. Nevertheless, the abundant fauna contained representatives of many zoological types. Some species already showed signs of the tendency toward the great proliferation and diversification that would occur during the Mesozoic era.

On the other hand, some groups of organisms became extinct before the beginning of the Mesozoic. The extinction of the last trilobites, the *Phillipsia*, marked the end of the Paleozoic era. The tetracorals lasted until the end of the period and were replaced in the Mesozoic by the hexacorals (of different origin), which are still present in the seas of today. The invertebrates, generally speaking, thrived with characteristic species and genera in the Permian seas; *Richthophenia*, a degenerate form of brachiopod, was adapted to a rocky marine environment. *Productus horridus*, another brachiopod, had a shell 20 cm (about 8 in.) wide. The gastropods, in temporary regression, were represented by the characteristic *Bellerophon*, with its planospiral winding, which is found in numerous Alpine rocks. The ammonites, whose first representatives appeared during the Carboniferous, were beginning to flourish; their lobar lines, which were starting to branch out into complicated designs, serve as an index of the fantastic evolutionary explosion that would take place during the Mesozoic era.

With the extinction of the ostracoderms and the placoderms (the armored fish that typified the first part of the Paleozoic era), marine fauna took on a more modern appearance. The cartilaginous selachians were quite common in the Permian seas; the *Pleuracanthus*, with its pointed, triangular tail fin and long cephalic spine turned toward the rear, was a representative selachian. The crossopterygians (lobe-finned fish) and the dipnoans (lungfish), which were also very common, serve as evidence of the unity of the continent of Gondwanaland. One example of the lungfish is found respectively in South America, in Africa, and in Australia. This phenomenon can be assumed to be a probable indication of the erstwhile connection of the three continental landmasses.

The amphibians attained their maximum development during the Permian period. These organisms descended from the crossopterygians during the Upper Devonian and, coincidental with the explosive rise of the reptiles, began to regress at the end of the Paleozoic. The Permian amphibians included some large animals, quite different from the present-day representatives of the group. *Eryops* —with its length of 1.5 m (close to 5 ft.), its wide, flattened cranium, its numerous sharp teeth, its squat body, and short, fat tail—was more representative than all the other species of the typical amphibian form of Permian times. *Diplocaulus*, with its broad triangular cranium, had an even more grotesque appearance.

The reptiles, which seem to have evolved from the amphibians during the Carboniferous, began to establish themselves during the Permian. Skeletal remains of an interesting animal, *Seymouria*, have been discovered in Permian rocks in Texas. *Seymouria* has been classified as a transitional organism, somewhere between the amphibians and the reptiles. This curious animal demonstrates that, because of the complexity of evolutionary lines, traditional organisms can coexist with both their ancestors and their descendants. *Seymouria* measured about 1 m (about 3 ft.) from one end of its lizardlike body to the other; its cranium was very similar to that of the stegocephalic amphibians from which it evolved, while its body was very much like that of a reptile. The problem of classifying this animal lies in the fact that its habits are unknown; scientists do not know with certainty whether *Seymouria* laid an amniotic egg, as reptiles do, or returned to the water to lay its eggs, as amphibians do.

The reptiles were already abundant during the Permian, but they had not yet gained the position of dominance they would have in the Mesozoic era. One reptile, the mesosaur, presents a classification problem, because its position in the evolutionary scale is uncertain. The mesosaur was a freshwater reptile, measuring about 30 cm (about 12 in.) in length. Fossil remains of this organism have been discovered both in South America and in Africa, thus providing further evidence of the existence of Gondwanaland. Because it was a freshwater reptile, its migration between Africa and America, across vast stretches of sea, was clearly impossible.

The pelycosaurs were represented by such notable animals as *Dimetrodon* and *Edaphosaurus*. These organisms were typified by very long neural spines that are thought to have served as supports for a membrane that permitted evaporation and, therefore, served a heat-regulating function suited to life in subdesert climates.

Later in the Permian period, the therapsids, such as *Moschops*, evolved from the pelycosaurs. The limbs and limb girdles of the therapsids were modified for four-footed mammalian locomotion, and the skull had a single opening in the temporal region. In due time, the mammals would evolve from this line.

1a

1b

THE MAIN LINES OF EVOLUTION

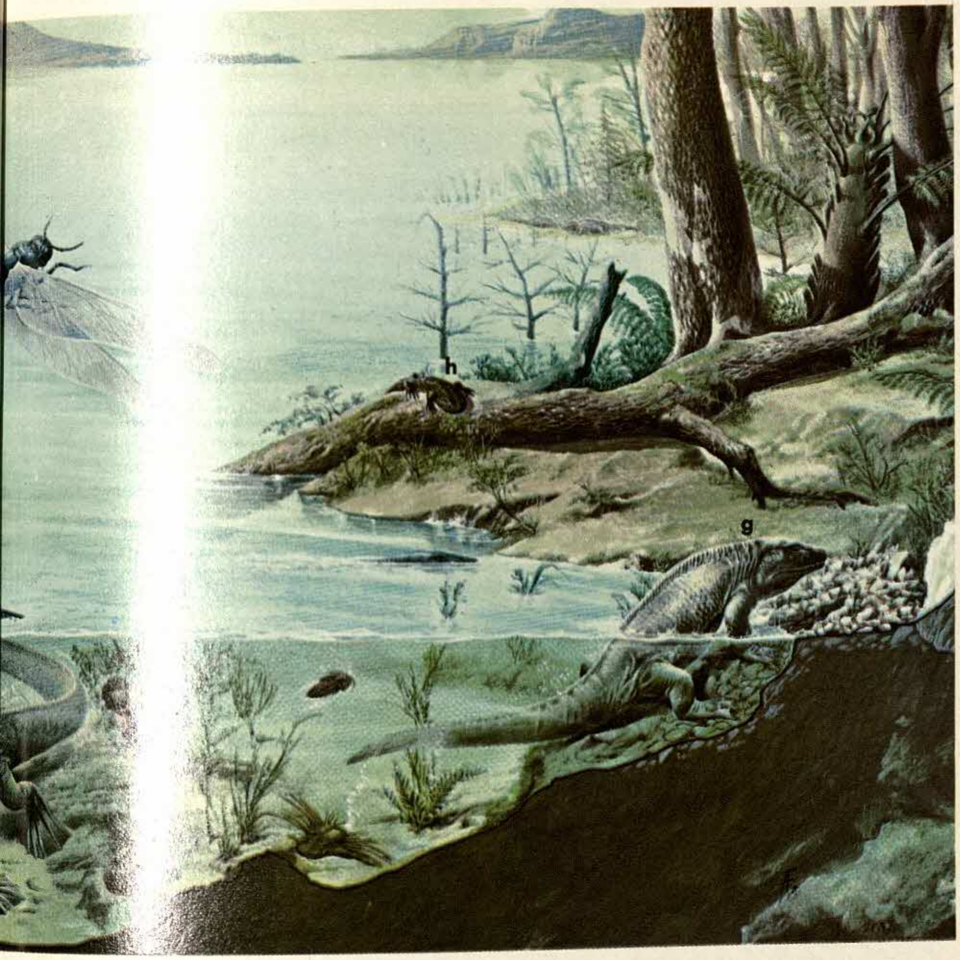
The history of life is a story of constant combat. New species gradually appear and overpower existing species. In large measure, the success of each new species results from the greater efficiency made possible by improved structures that are more congruous with the environment and better adapted to ecological conditions. Modern biology furnishes many examples to demonstrate that biological equilibrium is extremely delicate and that the introduction of a simple modification is sufficient to produce immediate and far-reaching changes.

For example, as a consequence of the opening of the St. Lawrence Seaway connecting the Great Lakes with the Atlantic Ocean, a new fish species was introduced into the Great Lakes. The new species, in open competition with already existing species, has caused the almost total disappearance of certain long-time inhabitants of these lakes. Sometimes the biological equilibrium can be shaken even by an apparently insignificant event; for example, the disappearance of an insect may, in turn, cause the extinction of some higher species, or the disappearance of an animal may consequently alter the plant composition of an environment.

Logically, the appearance of a new species is not always accompanied by the destruction of a preexisting one; some species have survived the appearance of others by finding ways of isolating themselves and resisting the biological pressures exerted by the invaders. Later, some such species disappeared, but they did so as a result of the phenomenon of involution or the weakening of the species itself.

The paleontological history of living organisms must take into account all these factors, or at least all those factors that have been deduced from the fossil evidence available. A detailed recounting of all the changes obviously is prohibited by space limitations. This examination, therefore, is limited to a few important changes, those related to the appearance of a new species that is particularly well adapted to its biological and ecological environment.

The history of life may be subdivided into different periods according to the evolutionary state of the living forms



THE PERMIAN LANDSCAPE—Some of the more common vertebrates of the Permian period are shown in Illustration 1a. Obviously it has been necessary in the reconstruction to condense the ecological conditions of the different environments. There were very dense forests, savannas, and swamps; many different animals lived on the Earth, although few species known today existed. In the center foreground, *Edaphosaurus* **d** is shown nibbling plants, while in the background two *Dimetrodons* **b, c** are depicted with their dorsal sails raised. These pelycosaurs and the mammallike *Moschops* **e** lived in a subdesert climate. *Cacops* **f,** a large stegocephalian amphibian, is shown climbing out of a pond in the right foreground. Finally, another reptile, *Araeoscelis* **a** is depicted on a rock in the left foreground. The vertebrates had probably not yet conquered the air; its only inhabitants were flying insects. As far as is known, these insects were almost identical to those of today —the chief differences occurring in their wing structures. Many nonflying insects, including cockroaches, populated the Permian landscape. Permian rocks in Kansas have yielded thousands of insect specimens.

The landscape in Permian times was ringed by mountains with glaciers that descended and invaded the plains, a sign that the climate —at least at certain times and in certain places—was cold.

Illustration 1b shows a lake in which lived both large stegocephalian amphibians, such as *Diplovertebron* **g,** and small amphibious animals, such as *Protriton* **h.** Other residents of the lake were the first freshwater reptiles, represented by *Mesosaurus* **i,** the sole representative of a group that is difficult to classify. Brachiopods and crinoids were similar to those found in the previous period. The seas held many species of gastropods and crustaceans.

and their organization. In the earliest periods, all living organisms had to adapt themselves to a fluid environment containing substances that were easily assimilable. The organisms were, structurally speaking, very simple—being unicellular for the most part—and, lacking the capacity to detect their food or to approach it directly, they assimilated their food directly from the water.

At a later date, plants and animals acquired multicellular forms, but these organisms also were stationary, having to remain immobile and wait for the movement of the waters to carry food in suspension or solution toward them. At a certain point in time, however, organisms developed nerve fibers that were quite simple in the beginning, but that gradually evolved into more complex structures. The more specific these structures became, the greater was their importance. In fact, the nerve endings evolved in time into sense organs and, later, into a center for elaboration of the sensations, the brain.

From an evolutionary point of view, many geological periods passed before the function of the brain became predominant—and then it was only in the mammals that intelligence assumed a fundamental role in life. In mammals—as opposed to all other vertebrates, almost every act of the individual is influenced in some degree by the cerebral cortex. The mammal is able to profit by experience to a far greater degree than other animals can. Mammalian behavior is, thus, less instinctive than that of other animals. The ability to solve problems appears sporadically and weakly in some lower mammals. This superior aptitude did not reach its highest level until the evolution of man.

In the meantime, living organisms gradually took on the forms with which most people are familiar today. The conquest of the emerged lands was of primary importance in evolution. In fact, only after the animals had left the water did they develop new means of locomotion, food assimilation, defense, and reproduction—to mention a few of the adaptations that became necessary for terrestrial survival. In the Permian period, terrestrial life-forms were already delineated; that is, the main lines of evolutionary development had been established for animal organisms that populate the continents of today.

THE MESOZOIC ERA

when reptiles dominated the Earth

The history of the evolution of the Earth's crust reached an important turning point during the Mesozoic era. This era is called the Mesozoic because the organisms living during this time possessed characteristics halfway between the primitiveness of the preceding eras and the higher organization of the subsequent era. The Mesozoic lasted only about 135 million years and included the time between the end of the Permian period, some 205 million years ago, and the beginning of the Tertiary era, about 70 million years ago.

The more recent biological and geological phenomena are, the greater and more detailed man's knowledge of those phenomena is—and the more feasible it is to divide and subdivide the geologic time periods. Almost every book on geology treats at length the connection between the various thicknesses of the sediments deposited on the sea floor during different eras. It is difficult enough to judge precisely how much sediment was deposited during any given era, but it is nearly impossible to know what percentage of the Earth's crust this sediment represents. Therefore, this discussion will be limited to a consideration of the absolute thicknesses of sediments and will avoid proportional comparisons of the lengths of various eras, periods, and epochs.

Given man's present knowledge, the task of subdividing the 155 million years of the Mesozoic era has been relatively easy; but the task has resulted at times in unmanageable detail. The chief divisions of the Mesozoic are the three important periods: the Triassic, the Jurassic, and the Cretaceous. To subdivide these periods further is extremely difficult, inasmuch as each terrestrial region or great continent has its own nomenclature derived from local or regional features.

The Triassic period lasted about 45 million years; the Jurassic, its successor, also endured for about 45 million years; and the Cretaceous, the last period of the era, spanned about 65 million years.

It is possible to distinguish clearly between periods of the Paleozoic on the basis of fossil evidence and geological data; however, between the Permian and the Triassic, a subtle progression of changes led to continual biological and geological variations.

Even though vastly differing geological and biological phenomena existed between the Permian and the Triassic, flora and fauna changed gradually; in any case, no sudden changes occurred in any geological period. The only important difference was that, in the beginning of the Mesozoic era, at least, a decline in the rate of geological changes occurred. In place of the Permian eruptions there was a period of relative calm as the volcanoes slowly became extinct; volcanic activity, however, picked up again at the end of the era. Then the enormous orogenic movement that gave rise to the American cordillera was accompanied by a fracturing of the Earth's crust that, in turn, caused the extrusion or rise of magma. In some places, the magma broke through the surface to spread over wide areas. In other places, it formed subterranean lakes without surface outlets; in time, these enormous subterranean volcanoes solidified.

CONTINENTS, SEAS, AND SEDIMENTATION

The seas, which had retreated during the Permian period, began to spread over a wider area during the Mesozoic era. The melting of the ice caps brought much water to both continents and seas; furthermore, numerous areas that had previously been above sea level sank—probably as a result of both isostatic adjustment and continental drift—thereby bringing new seas into being.

Calcareous and dolomitic rocks, as well as such intermediate sedimentary rocks as gypsum, marl, sandstone, and conglomerate, were formed with greatest frequency. These kinds of rocks, more than most other kinds, are easily subject to great change, especially if they lie deep underground or remain submersed for long periods of time. Recrystallization processes, pressure, and heat may change the structure of these rocks into a more homogeneous form than before, thus destroying for the most part any fossils.

THE CONTINUED EVOLUTION OF LIFE

The Mesozoic era has often been called the Age of the Reptiles or the Age of the Dinosaurs, for it was during this era that reptilian forms became the dominant vertebrates on the Earth. The reptiles evolved from aquatic and amphibious organisms, differentiating greatly in number, size, structure, and habitat.

Some Mesozoic reptiles, apparently becoming dependent on aquatic life for their food, evolved fishlike forms that enabled them to survive in water but made them unsuitable for terrestrial life. Others, including the largest land animals ever to inhabit the Earth, spent much of their lives wading in shallow bodies of water, browsing on aquatic plants. Supposedly, the buoyancy of the water helped to support their great weight, which probably reached 50 tons in such animals as the ponderous brachiosaurs. Still other reptiles evolved structures that enabled them to glide through the air and even to fly. Certain kinds of dinosaurs came to walk on their hind legs and carried their bodies more or less erectly; in such species the forelimbs generally were greatly reduced in size. The variety of adaptations exhibited by the reptiles was enormous.

The Triassic and Jurassic were the periods most completely dominated by the dinosaurs, although these reptiles survived throughout the entire Mesozoic era. Nevertheless, for reasons not completely understood, the dinosaurs disappeared completely at the end of the era. The reptiles that survived into the subsequent (Cenozoic) era were, for the most part, small or medium-sized animals similar to present-day reptiles. Certain crocodilians and the giant Komodo lizard of Indonesia represent the largest modern descendants of the monster reptiles of the Mesozoic.

If the reptiles were the dominant vertebrates of the Mesozoic era, the ammonites were the dominant invertebrates. In common with the dinosaurs, these external-shelled cephalopods underwent very rapid change and diversification; they spread widely throughout the Mesozoic seas, increased remarkably in numbers—and became extinct by the end of the era.

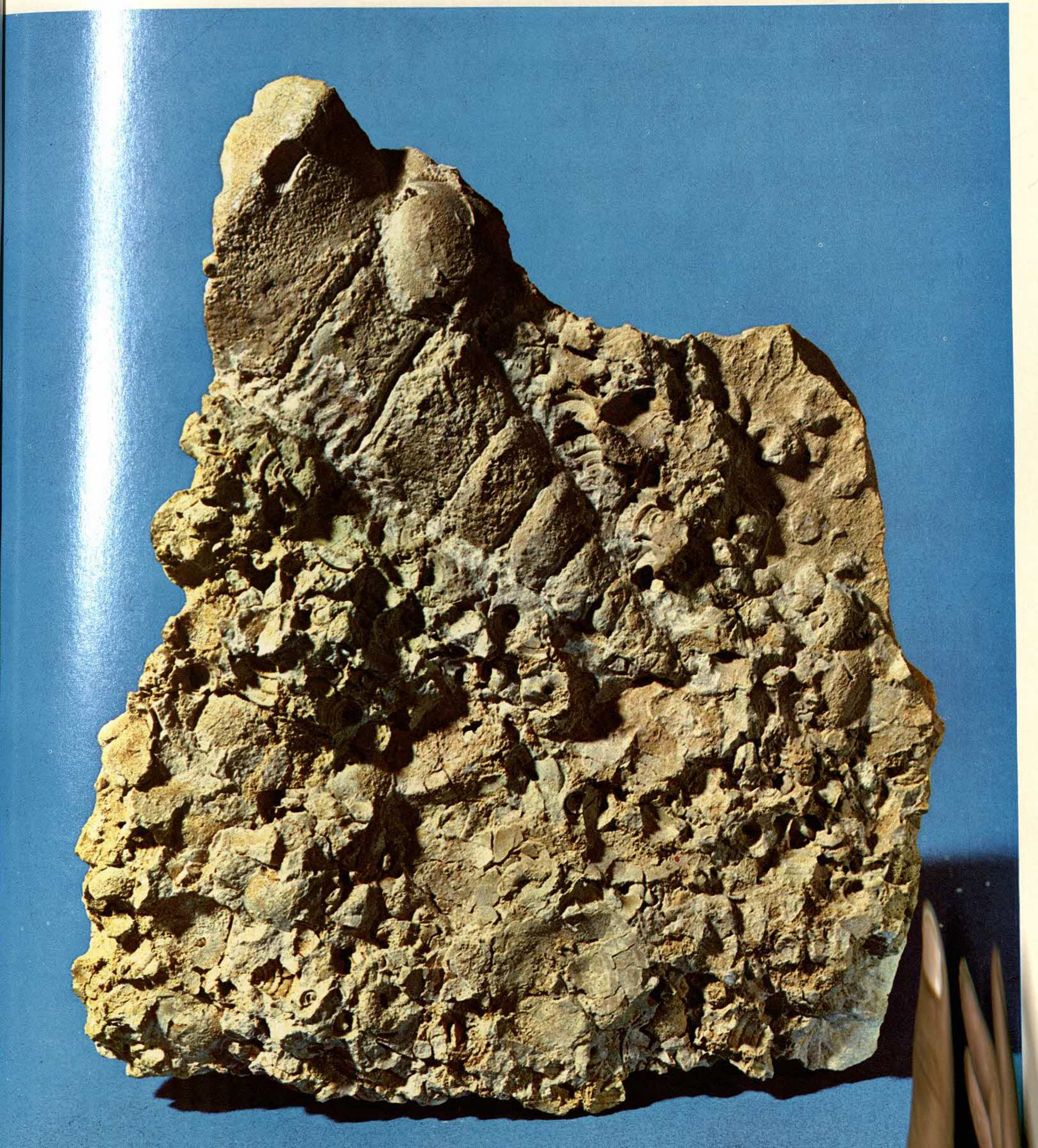
In spite of the dominant roles played by the reptiles and ammonites, the Mesozoic was marked by many other important evolutionary changes. Insects, for example, spread into every conceivable environment and diversified into an enormous number of species; but it is impossible to trace their evolution in detail because they were most unlikely to be preserved and most of their remains have been lost. Nevertheless, some Jurassic rocks contain representatives of ants, bees, butterflies, cockroaches, dragonflies, flies, moths, wasps, and many others.

Still other flying animals, the birds, date from the Mesozoic era. These ancient birds had primitive organs, including barely functional feathers and often extremely long beaks—the latter sometimes containing rows of pointed teeth similar to those of their reptilian relatives.

The mammals consolidated the position that they had attained toward the end of the Paleozoic era, evolving continuously toward more highly perfected forms that eventually would lead them toward mastery of the land. The first marsupials appeared during the Mesozoic, and placental mammals began to develop. For the most part, however, Mesozoic mammals remained rather small and undistinguished.

The dominant plants of the Mesozoic were the cycads. The most significant change in the Plant Kingdom, however, was the appearance of angiosperms of flowering plants.

TRIASSIC FOSSILS—Together with smaller gastropod fossils, this rock contains a well-preserved fossil of *Chemnitzia undulata.* The rock was found in Königslutter, Germany.



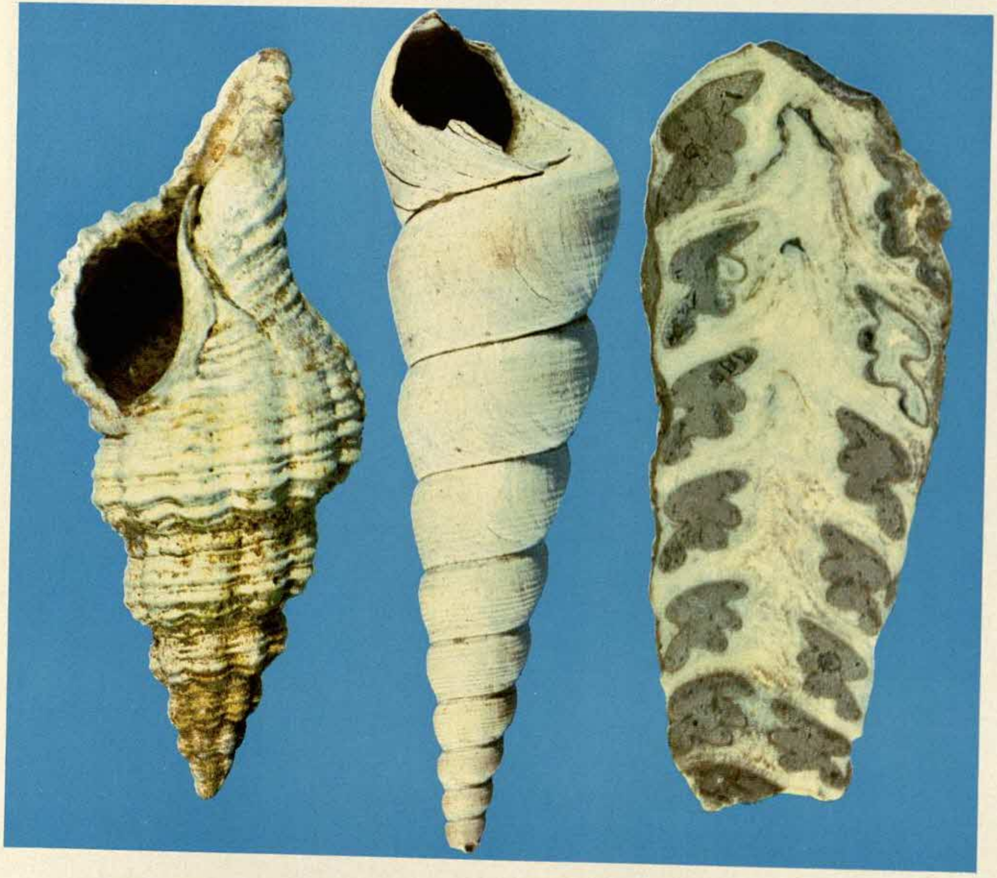
THE MOLLUSKS | soft bodies, hard shells

The Phylum Mollusca is represented in the geological record by thousands of fossil species distributed from the Cambrian period (almost 600 million years ago) to the present. The complexity of even the earliest mollusk fossils in the

---

PATTERN OF THE SHELL—The varied shell patterns of the mollusks are useful in classifying the fossil forms, for the soft parts of the body rarely are preserved. The shell may be completely smooth with only light streaking marking its growth, and with more or less marked ribbing or with large folds. The illustration shows two main types of pattern; one axial, where the elements are parallel to the axis of the shell (Illustration 1a, *Fusus crispus* of the Pliocene), and one spiral if the elements are parallel to the curl of the spirals (Illustration 1b, *Turritella* of the Pliocene). Pattern has evolved through time from smooth forms to more corrugated ones. A mysterious group of fossils, adapted to rocky coast life and now completely extinct, the Nerineacea, have patterns on the inside of the shell (Illustration 1c).

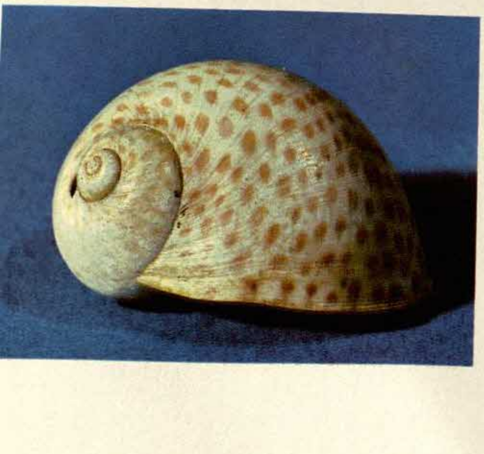
1a 1b 1c



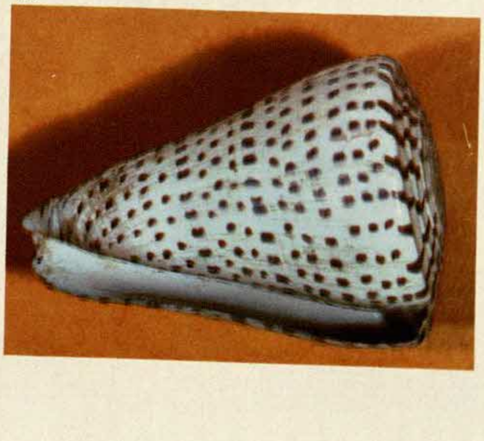
SHELL COLORING—The shells of many living gastropods, especially those of warm seas, are vividly marked. Their coloring and geometric designs make them highly prized by collectors.

Fossil shells with traces of original coloring are rare, but a few colored specimens (Illustration 2a) are known among the gastropods of the Pliocene epoch. Older forms probably had coloring similar to those of today. Living members of the genus *Conus* (Illustration 2b) have obvious coloration that is completely missing in fossil specimens.

2a



2b



3a

3b

3c

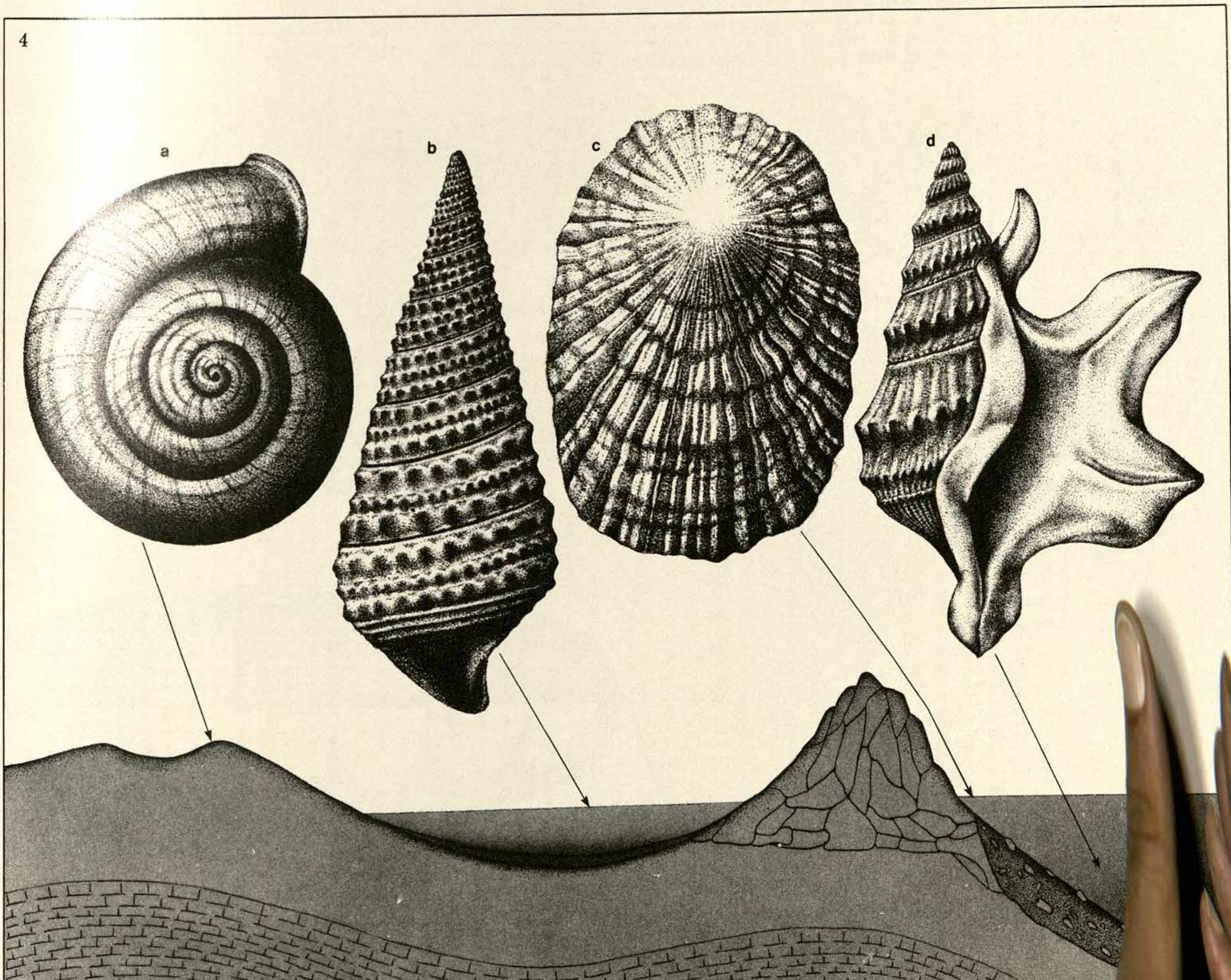
CLIMATIC INDICATORS—Because some gastropods can live in only certain temperature ranges, the presence of fossils of these species in geological deposits gives strong indication of the climate prevailing at the time of deposition. Among the cold climate types is *Crysodomus sinistrorsus* (Illustration 3a), notable for the counterclockwise turning of the helicoidal shell. *Strombus bubonius* (Illustration 3b) and *Patella ferruginea* (Illustration 3c) also lived in cold climates.

Cambrian suggests that they were preceded by a line of simpler ancestors in Precambrian time. Some groups of mollusks became extinct, but today six classes exist. They range in form from snails with coiled shells, to clams with shells composed of two valves, to squids with small internal shells. The six classes are: (1) Monoplacophora; (2) Amphineura (chitons); (3) Gastropoda (snails, slugs, whelks); (4) Scaphopoda (tooth shells); (5) Pelecypoda (or Bivalvia, the clams and oysters); and (6) Cephalopoda (squids, octopuses, cuttlefish). The two latter classes are discussed in articles beginning on pages 116 and 108, respectively, of this volume.

The Monoplacophora once were known only as fossils and were previously believed to have become extinct 350 million years ago. Then on May 6, 1952, 10 living representatives of the group were dredged from a depth of 3,570 m (about 12,000 ft) in a deep ocean trench along the Pacific coast of Costa Rica. At first, the animal was thought to be a gastropod, for its shell resembled that of a gastropod. Unlike a gastropod, however, its internal soft parts are not coiled. It was named *Neopilina galathea,* and it was placed in the class Monoplacophora. Since 1952 other living species of *Neopilina* have been discovered in Pacific waters from Baja California to Peru, in the Gulf of Aden, and along the eastern coast of South America. One of the primitive features of *Neopilina* is the bilaterally symmetrical arrangement of the internal organs. Most other mollusks show some degree of torsion or twisting of the internal parts. Neopilina possesses paired muscles, the scars of which are clearly visible on the inner surface of the shell. This pairing of muscles is suggestive of segmentation, a feature otherwise unknown among the mollusks but typical of the annelids (earthworms and their relatives). The discovery of *Neopilina* strengthened the belief that the mollusks and annelids share a common ancestry.

Chitons are all marine, and they live on rocky shores to which they can cling tenaciously. The shell, which covers the dorsal surface of the animal, is composed of eight plates that articulate with each other and permit the folding of the shell completely around the animal when it is disturbed. Because the plates separate from each other after the death of the animal, fossil chiton shells are not

ENVIRONMENTAL RECONSTRUCTION—Fossil gastropods are extremely useful for reconstructing the probable environments of the past. With a knowledge of the normal habitat of these animals today and on the hypothesis that they behaved similarly during the geological past, it is possible to draw conclusions about the habitats in which the animals lived. In this way, the genus *Apherrais* (Illustration 4d) indicates a sandy marine bottom, the genus *Petella* (Illustration 4c) a rocky one, the genus *Helix* (Illustration 4a) a continental environment, and the genus *Cerithium* (Illustration 4b) a brackish environment. If a sufficient variety of fossils becomes available, it then is possible to reconstruct the different environments over a wide geographic area. The presence of marine fossils on mountaintops is one piece of evidence that these mountains have risen from the sea.



found preserved intact. Chitons are an ancient group, some fossils dating back to the Cambrian period.

The gastropods comprise the largest group of mollusks, and they occupy several habitats: marine waters, fresh waters, and land. The terrestrial species generally require a moist habitat to survive and reproduce. Nearly all have shells; the common garden slug is an exception. The embryos of present-day gastropods develop small, simple, cap-shaped shells; as the shell grows, it develops into the larger, often more complex shell typical of the adult.

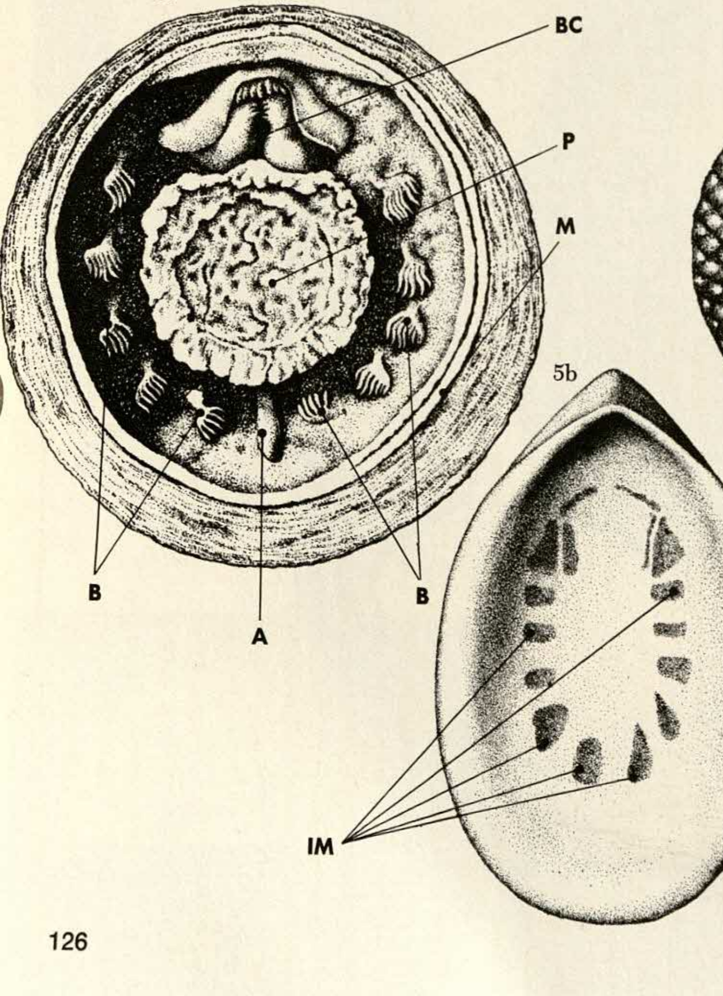
Limpets have conical shells, some of which are very low cones. Snails typically have coiled shells. In a few species the shell is planispiral; that is, the coil is confined to one plane. In others it rises into a conispiral that may range from a very low helix to a tall, slender one. It is believed that the earliest gastropods had simple cap-shaped shells, and that the planispiral shell evolved from this. The conispiral shell is still more advanced. Some shells are highly ornamented by spines, ridges, and colored patterns. Except for the color, which tends to disappear in fossils, the characteristics of the shells are important features used in the identification of fossil specimens.

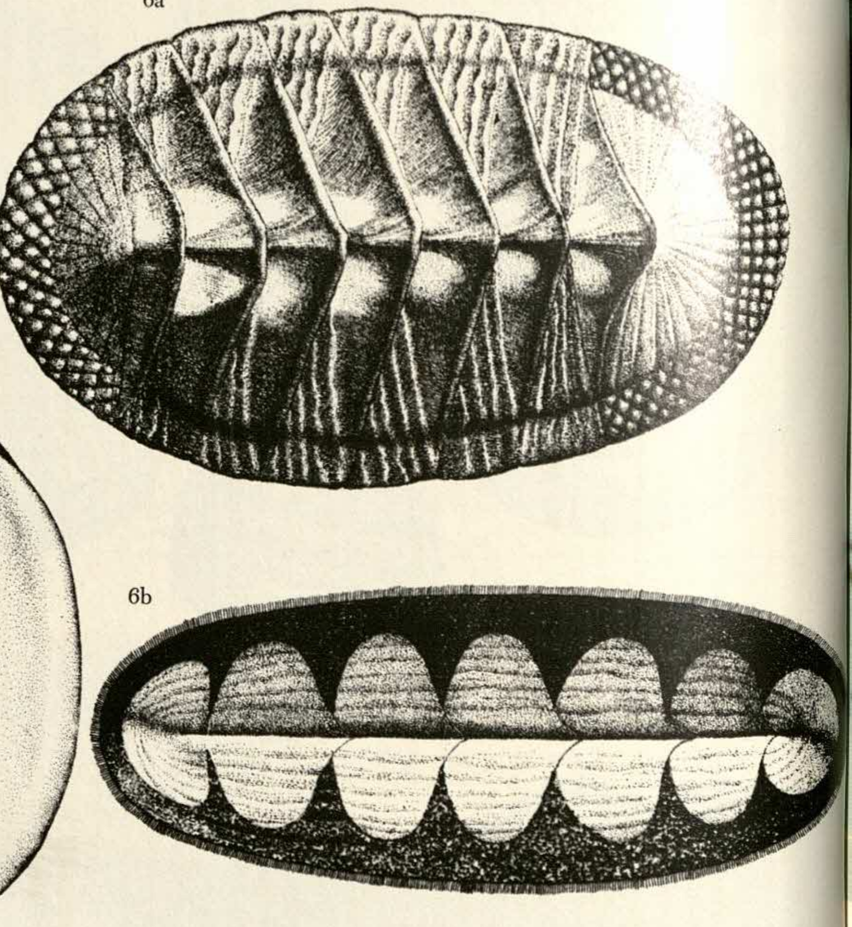
Gastropods are among the oldest of the mollusks, some specimens having been discovered in early Cambrian deposits. Because of their great variety of shapes, their diverse habitats, and their great geological age, fossil gastropods have proved useful as index fossils. Those that lived during only one geological period can be used to date the rocks in which they are found. Others serve as indicators of climate or habitat in the regions in which they once lived. This information is available only in the case of species still living or that closely resemble species still living, for the soft parts of the animals rarely are preserved, and the shell alone may yield little information about its former occupant.

The scaphopods have curved, tubular shells that superficially resemble the long canine teeth of carnivorous animals. The shell, which usually is no longer than 15 cm (about 6 in.), is open at both ends. These burrowing marine animals live in the sand or mud of ocean bottoms. The oldest fossil shells come from the Ordovician period and thus are no older than 500 million years.

MONOPLACOPHORA — The Monoplacophora are characterized by univalve shells in the form of a hood. The soft parts have no internal coiling as have snails and other gastropods. Shown is a living specimen of *Neopilina galathea* (Illustration 5a) with the details of its internal anatomy: the mantle **M,** the foot **P,** the series of gills **B** all around, the mouth **BC,** and the anus **A.** The most interesting feature is the bilateral symmetry that is correlated with the absence of coiling. Next to it is the inside of the shell of a fossil specimen, *Pilina unguis* (Illustration 5b) of the Upper Silurian (about 400 million years ago), in which the bilateral symmetry is clearly evident not only in the overall shape but also in the arrangement of the muscle imprints **IM.**

THE AMPHINEURA—The chitons comprise the small class Amphineura whose fossils are relatively uncommon and whose present representatives are of less importance than the much more numerous Gastropoda, Pelecypoda, and Cephalopoda. Chitons are marine animals found at every depth in all seas. They are characterized by a shell of articulated plates that cover the dorsal surface of the body. The most ancient representatives are from the Ordovician (Lower Silurian) of Scotland and are not appreciably different, either morphologically or anatomically, from existing species. Represented in Illustration 6b is *Gotlandochiton,* a genus 350 million years old. It is not substantially different from the present-day chiton (Illustration 6a).


5a
5b


6a
6b

THE TRIASSIC PERIOD

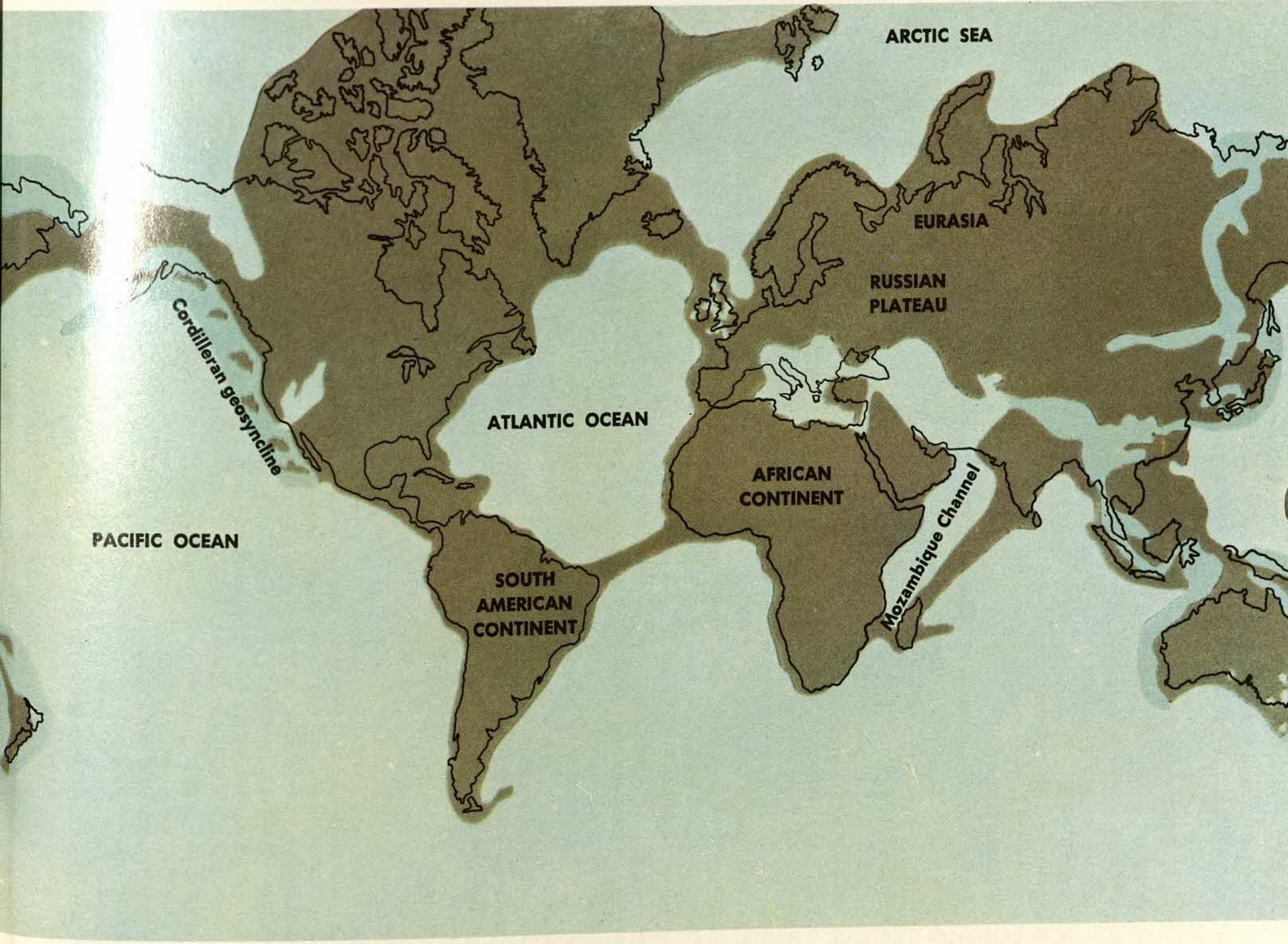
the Earth at the beginning of the Mesozoic era

The first great period of the Mesozoic era is called the Triassic. This name is derived from the three chief divisions of rocks from the period—rocks found in central Germany, where the first detailed studies of early Mesozoic deposits were conducted. One characteristic of the Triassic and subsequent periods of the Mesozoic era was the intense and varied sedimentation phenomena that occurred. In contrast with preceding periods, the Triassic was populated by abundant and characteristic fauna. The existence of varied deposits, replete with distinctive fossil associations, has made possible the temporal subdivisions of the Triassic into various epochs and ages. Moreover, the existence of these fossil-rich deposits gave rise to the development of flourishing schools of geology and paleontology in Switzerland, Ger-

THE GEOGRAPHY OF THE TRIASSIC—This map indicates the appearance of the emerged lands and the seas of the Lower Triassic period. The emerged lands were similar to those of the Upper Permian. The two American continents were still joined by land bridges to Europe and Africa, respectively. It must be remembered, however, that the inclusion of these bridges on the map is completely hypothetical inasmuch as they have been superimposed on the present-day positions of the continents; continental drift probably played an important role in the establishment of these bridges.

The Uralian geosyncline had been filled in, but the Tethys Sea still connected the present-day Mediterranean with the Pacific Ocean.

The Alpine geosyncline originated during the Lower Triassic. A shallow sea extended across all the areas now occupied by the mountains. The sea was subject to frequent changes in coastline. An extremely rapid sedimentation occurred in this area. Thick marine strata were often formed, and they gave rise, in an extremely altered form, to the dolomitic rocks of the Tyrolean Alps.



many, and Italy near the end of the nineteenth century and the beginning of the twentieth century.

At the end of the Permian period ice caps covered extensive areas of the Earth, and the seas receded farther than in any other period in the Earth's history. These phenomena played significant roles in the rapid evolution of innumerable species of organisms, an evolution that at times produced monstrous forms.

During the Lower Triassic—that is, the most ancient part of the period—the most important event was the beginning of a period of marine transgression, in the course of which the seas covered numerous landmasses. Space does not permit a detailed recounting of the movements of the seas on all the continents; however, it is interesting to follow those movements that occurred in Europe and particularly in Italy. The division between the Permian and the Triassic can be discovered only in the regions where clear-cut geological events took place—events such as the appearance of emerged lands which the sea had formerly covered. Through the study of various fossil associations, geologists have distinguished among the deposits of various epochs and ages.

SUBDIVISIONS OF THE TRIASSIC PERIOD—This table shows the subdivisions of the Triassic period. The three epochs—Lower, Middle, and Upper—have names derived from particular rocks in Germany that were formed by sedimentation in shallow seas and lagoons. The epochs, in turn, have been subdivided into ages and named for geographical locations.

UPPER TRIASSIC (KEUPER)	**RHAETIAN**
	NORIAN
	KARNIAN
MIDDLE TRIASSIC (MUSCHELKALK)	**LADINIAN**
	ANISIAN
LOWER TRIASSIC (BUNTER)	**SCYTHIAN**
	SCYTHIAN

The distinction between the Triassic and the Jurassic is clearer than that between the Permian and the Triassic, because at the end of the Triassic the seas began to regain their predominant position over the emerged lands, a position that had been lost during the marine recessions of the Permian.

Two characteristics of the Triassic period, indicated by the nature of its flora, were the aridity of many regions in Europe and elsewhere, and the mildness of the climate. These climatic phenomena probably favored the development of the reptiles and the gigantic dinosaurs.

Geology strongly conditioned the biological environments; therefore, particular regions lend themselves to rather specialized studies. For example, the eastern Alps are ideal for the study of marine environments; central Europe, for the study of terrestrial and lagoon environments; and North and South America, for the study of terrestrial environments.

TRIASSIC ROCKS

The complicated sedimentation of the Triassic gave rise to marl, sandstones, limestones, and dolomites. These rocks, many of which were formed through marine sedimentation, constitute an important group. Some of the deposits laid down during the Triassic did not consist of small beds with modest thicknesses; rather they constituted mountainous massifs with thicknesses measuring more than a kilometer. Mountains in the Alps are studded with beautiful blocks that represent ancient islands formed of corals; their development testifies to a progressive sinking of the islands under the level of the sea. The rocks often contain traces of the skeletons or the thecae of these animals.

In addition, rocks of typically continental origin were formed during the Triassic. Some epicontinental rocks typically had their origins in evaporation. Throughout the entire Triassic period, salt lagoons were drying up, leaving thick beds of salt and gypsum.

Eruptive (igneous) rocks constitute a third type of abundant rocks found in the Alps, in Africa, and in North and South America. Many types of igneous rocks are found in Triassic formations; these include effusive lava rocks, porphyritic rocks, and melaphyres—signs of great volcanic eruptions. Tuffs are also found, sometimes as subaerial deposits and sometimes as underwater ones; the former were often deposited on lands where plants were growing and consequently these organisms were fossilized. In other places, the lands themselves are tuffaceous. Therefore, scientists can reconstruct the history of regions near volcanoes. They are able to determine where plants have been able to grow on land previously devastated by volcanic ash, and they can find evidence that more ash was subsequently deposited in the same regions, piling up in thick layers. Many tuffs were destroyed by erosion, and the particles comprising them were transported to new locations where they were deposited to form new rocks. In other cases, the transformation of tuffs began only in recent epochs. The magmatic activity of the Triassic was in part a continuation of the highly intense activity begun during the Permian period. The orogenic phenomena that occurred, although very slight, nevertheless are indicative of magmatic activity taking place at great depths. In turn the orogenic phenomena were accompanied by magmatic intrusions and volcanic eruptions.

MICROFOSSILS

symmetry and beauty

1

A FORAMINIFER—*Orbulina* (Illustration 1) is a planktonic foraminifer with a thin spherical shell perforated by numerous fine protoplasmic pseudopodia that increase its ability to float. Internal chambers can be seen within the shell. These organisms comprise part of the marine plankton of today.

Fossils come in all sizes—from the gigantic bones of a dinosaur or a woolly mammoth to the exquisite beauty of the preserved remains of ancient microscopic organisms. The fossils of these minute organisms are known as microfossils.

Soft parts of plants and animals are rarely well preserved after death, but hard parts sometimes persist for millions of years. Microorganisms with such hard parts include some protozoa (single-celled animals) and diatoms (a type of single-celled alga).

Foraminifera are amoeboid protozoa that secrete around themselves shells composed primarily of calcium carbonate. The shell has fine openings through which stretch slender pseudopodia (extensions of the cytoplasm of the cell). The pseudopodia, which branch and fuse with each other, are used in locomotion and in capturing food. As the cell grows, it adds new chambers to its shell, each chamber communicating with the previous chamber. In some species the new chambers are added in helical fashion, the shells eventually resembling that of a snail. In other species the shells are spherical, and in still others the chambers are arranged in a straight row. As many as a hundred chambers may be formed by a single cell. Many living foraminifers are barely large enough to be seen without a microscope, but some fossil species exceeded 2 cm (about 0.75 in.) in diameter.

The calcium carbonate shells of innumerable ancient foraminifera formed deep chalk deposits in several parts of the world; one of the most famous is the chalk cliffs at Dover in England. The limestone used in the Egyptian pyramids consisted largely of deposits of *Nummulites*, a foraminifer.

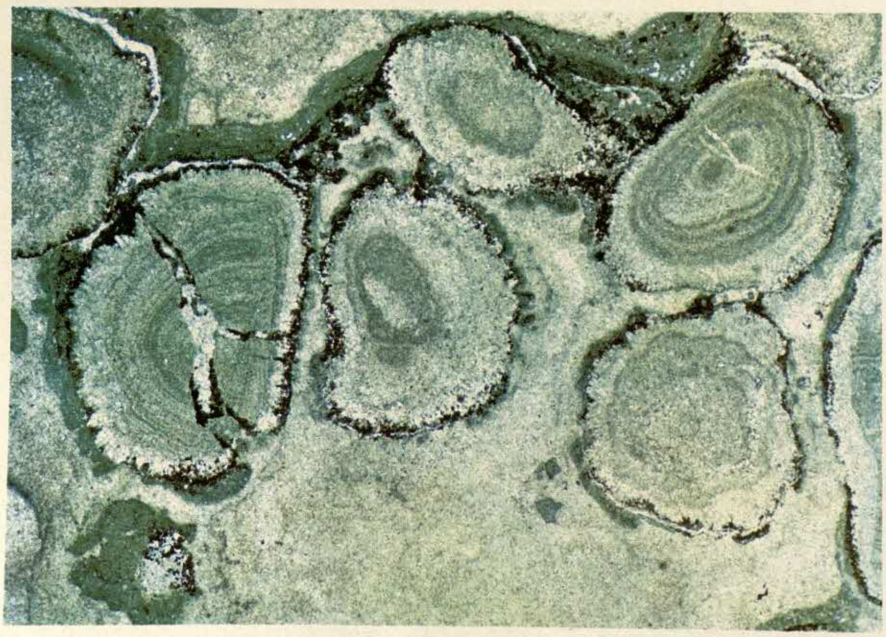
RADIOLARIANS AND DIATOMS

Radiolarians are another group of amoeboid marine protozoa. Their spherical shells contain silica, a compound extremely resistant to decomposition; a few species have shells composed of strontium sulfate. Long, stiff pseudopodia radiate outward through fine holes in the shells. Deposits of radiolarian shells on ocean bottoms are called radiolarian ooze, which occupies large areas of the Pacific and Indian oceans.

Diatoms are unicellular algae of a brown or golden-brown color. They have peculiar siliceous cell walls composed of two halves that fit together like a box and its lid. Like radiolarian shells, these cell walls are very resistant to decomposition.

Deposits of diatomaceous earth consisting largely of fossil cell walls were laid down in both fresh and marine waters. One deposit in California is about 1,000 m (about 3,000 ft) thick. Diatomaceous earth is mined for several commercial uses; for example, as a fine abrasive used in silver polishes and some toothpastes. At high temperatures it is a better heat insulator than asbestos; and in sugar refineries it is used to filter sugar solutions. Added to paint, it increases visibility at night and is used for traffic signs and lane markers. At one time it was added to nitroglycerin to help transport it with greater safety, but other material is used today. Another use of diatomite is as a filler or extender in paper, ceramics, bricks, plastics, soap, and detergents. It is used also for sound insulation.

2



STUDY METHODS—Because of the minute dimensions of microfossils, their study is carried out with a microscope. Two principal methods are used to separate the fossils from the matrix in which they are embedded. If the matrix is very friable, like clay, it is broken up simply by washing in water. The residue is then filtered to remove the larger particles, dried and placed under the microscope, where the fossils can be separated out with fine needles. After separation the fossils are placed in special containers and are ready for further study. The disintegration of hard rocks is carried out by immersion in hydrogen peroxide.

Some hard rocks, such as limestone, are ground progressively into sections so thin that they become transparent enough for the microfossils to be studied under the microscope. The illustration shows calcareous fossil algae of the Triassic period. (7 X) These thin sections have the advantage of showing the fossil in the position in which it was deposited, surrounded by other fossilized residue deposited at the same time. Such an arrangement often provides knowledge about the climate at the time of deposition.

Sections of specimens are oriented in different planes so that the fossil shape can be reconstructed after viewing several angles.

FAUNA OF THE TRIASSIC PERIOD

the beginning of reptilian domination

About 225 million years ago animal life on the Earth underwent rapid evolutionary changes. The extinction of the trilobites and tetracorals marked the end of the Paleozoic era and the opening of the Triassic period of the Mesozoic era. The ammonoids, of great importance from a stratigraphic point of view, were in full development. Pelecypods (bivalved mollusks), poriferans (sponges), gastropods (snails), and hexacorals were also plentiful. Members of the genus *Ceratodus* were still very common among the fish, which conserved many of their Permian characteristics. The continents were populated chiefly by amphibians and reptiles.

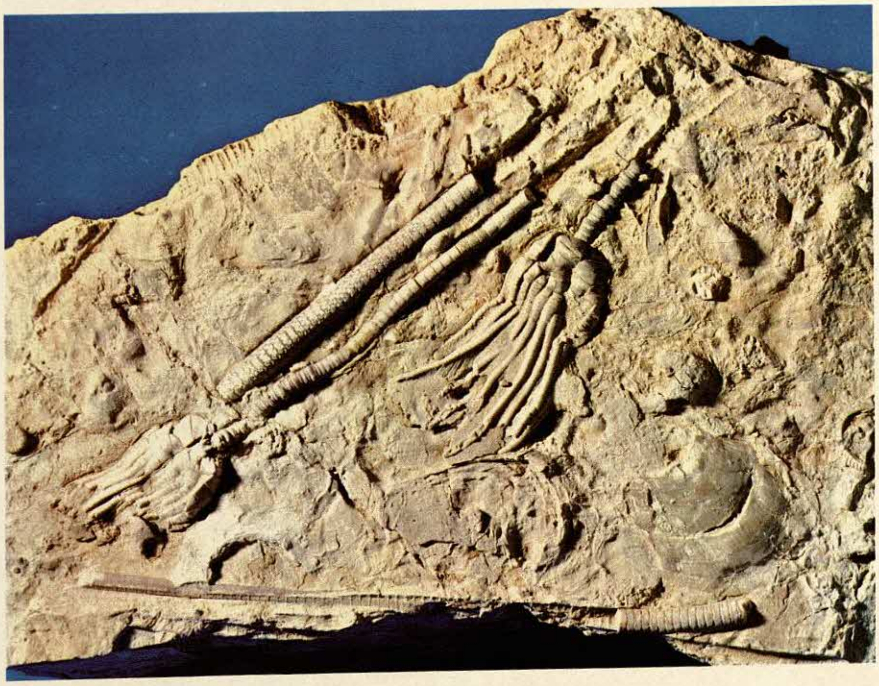
The most outstanding occurrences of the 45-million-year Triassic period included the further development of the amphibians, which reached their largest dimensions and greatest distribution; the appearance of the first dinosaurs; the invasion of the marine environment by the reptiles, and especially the appearance of several forms from which the mammals seem to have evolved. The latter was the most important event of the Triassic period.

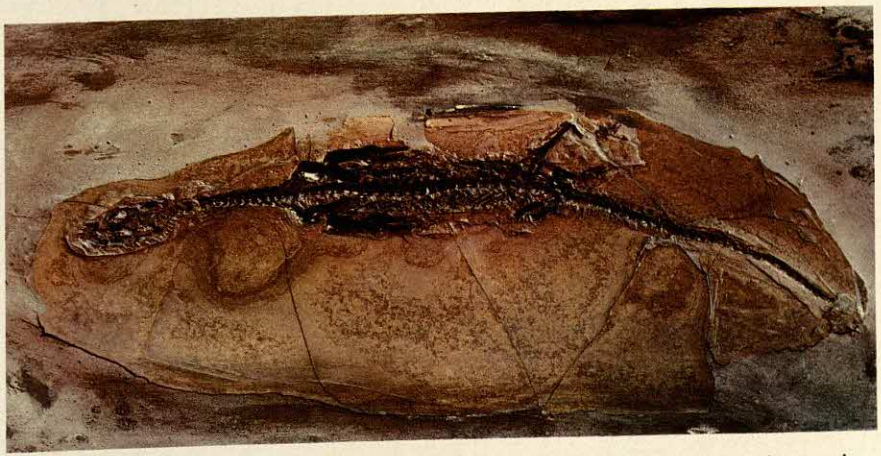
THE SAURIANS INVADE THE SEAS

Starting with the rocks of the Triassic period, specimens of fauna destined to become highly developed in the following period occur more and more frequently. No sooner had the vertebrates evolved from aquatic animals to land dwellers than some kinds returned to aquatic habitats. A division occurred among the Reptilia: one branch followed the path of terrestrial evolution and gave rise to an extensive group of dinosaurs and other typically terrestrial reptiles (which were often, however, excellent swimmers, living near the sea or in swamps and lakes); the other branch followed the course of aquatic evolution and led to the development of forms that were as well adapted to the water as any fish. The cotylosaurs, for example, can be considered the ancestors of the ichthyosaurs, which would come to dominate the seas during the following Jurassic period.

Numerous forms of marine reptiles appeared at the beginning of the Triassic period, although the more highly evolved forms were typical of the Jurassic. It might be said that of all the reptiles, the ichthyosaurs, structurally speaking, were the best adapted to an aquatic life; indeed, the term *ichthyosaur* means *fish-reptile*. The fact that these animals had such highly specialized structures seems to imply that they had evolved from very ancient forms. Nevertheless, among all the species known from the Permian, no form has ever been discovered that could be linked with these aquatic reptiles.

ENCRINUS CARNALLI—Crinoid fossils are found typically in Triassic limestones. The specimens illustrated come from Muschelkalk, a limestone very rich in crinoids.



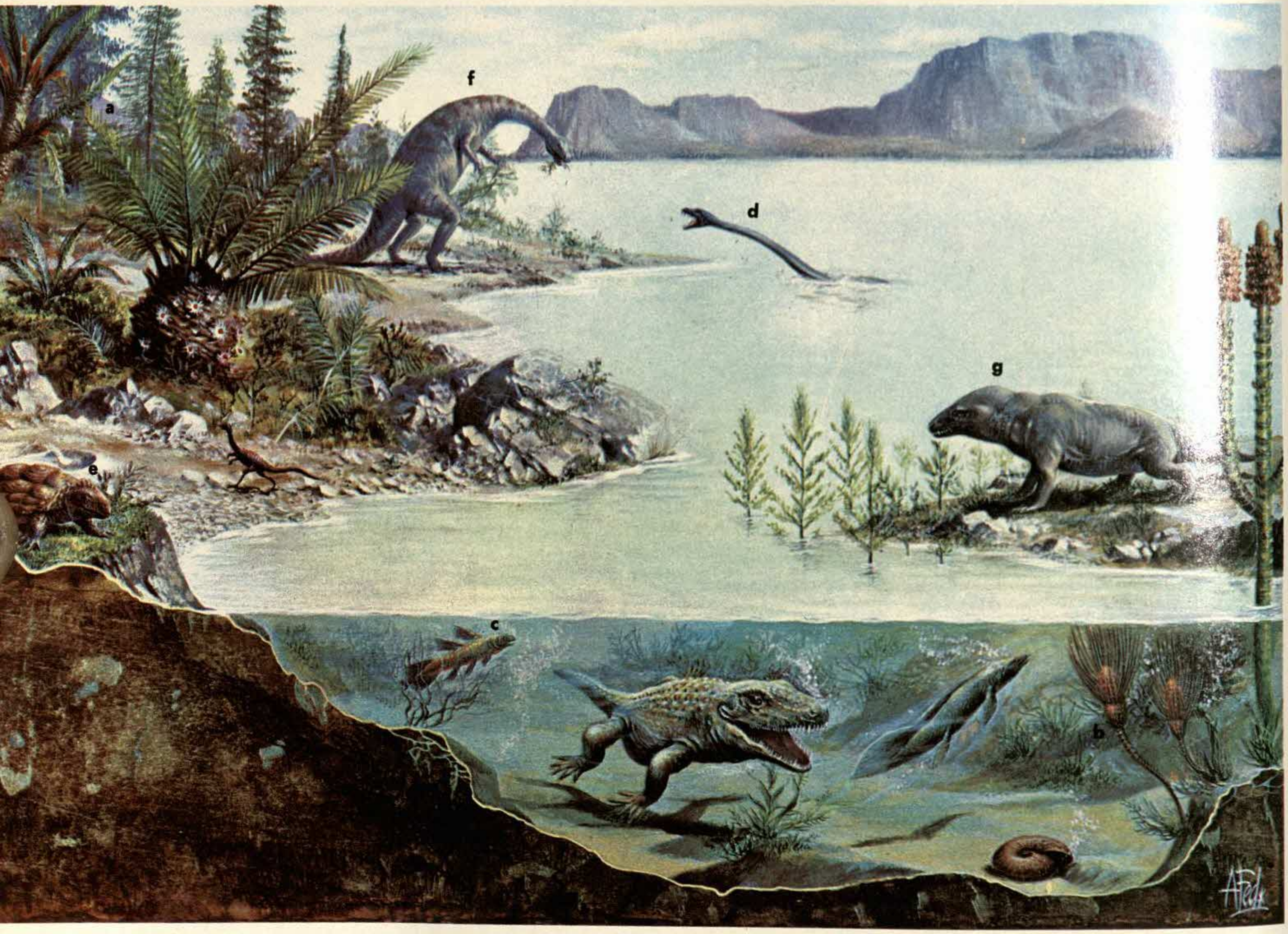


PACHIPLEURA—This organism belonged to the Nothosauria, an interesting group of amphibian reptiles that appeared at the end of the Permian. The better-known and more characteristic forms are found in formations of the Middle Triassic.

THE TRIASSIC LANDSCAPE—The plant which dominated the Triassic landscape was the *Voltzia heterofilla* **a;** this was a gymnosperm that was very similar to present-day gymnosperms. The sea bottom in shallow waters was populated by various types of algae. Colonies of mollusks lived among them or on the bare sea floor. Off the rocky shores, where the waters were clean and constantly moved by currents, tides, and waves, numerous hexacorals and other colonies of building animals thrived. Often the mollusk-type fauna was highly abundant; on the bottoms both fixed and mobile echinoderms **b** with very beautiful forms existed. Fish swam rapidly through the water even though they were still relatively primitive. Among these were the coelacanths **c,** some of which still live today, having somehow escaped extinction. The sea also contained reptiles **d** that had become adapted to marine life.

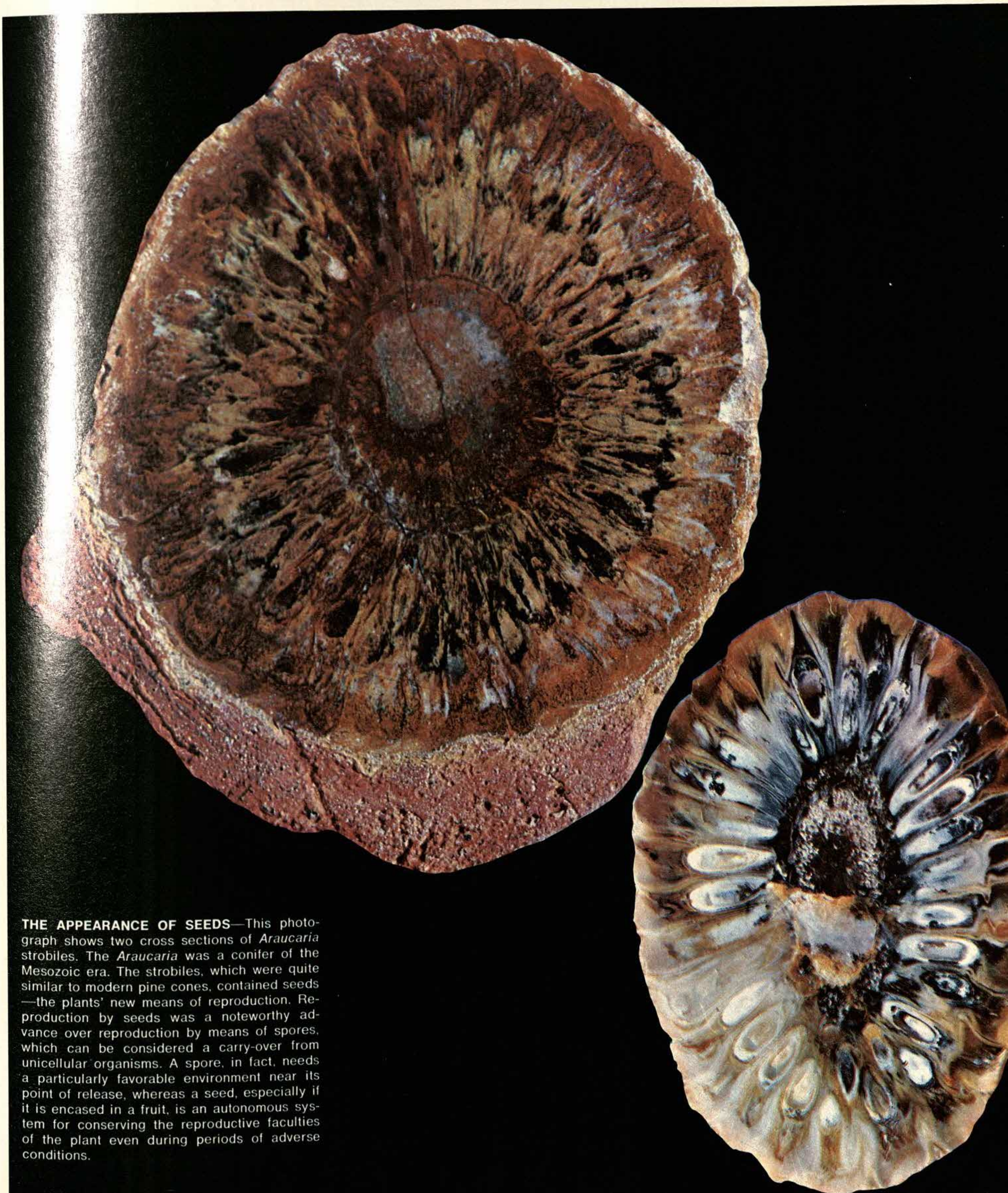
The most interesting organisms of the Triassic were found on land. On the dividing line between the water and dry land could be found turtles **e,** which were already divided into terrestrial and aquatic forms; at the beginning of their existence, the turtles invaded both environments indiscriminately. The most interesting phenomenon on land was the appearance of the dinosaurs **f** that walked more or less erectly on two limbs. Forms with atrophied or relatively undeveloped forelegs already existed; at the same time, great development of the hind legs easily compensated for the diminution of the front legs. The hind legs were used mainly for locomotion; they were aided in part by the huge tail, which rested on the ground. The trend toward gigantic forms continued; soon the dinosaurs, which in the Jurassic would become the masters of the emerged lands, grew as tall as houses and had an enormous destructive power—so much that they actually determined the types of animals in the areas under their sway. Furthermore, their powerful offensive weapons, in time, were to be matched by the appearance of equally terrible defensive weapons. For the time being, however, the bodies of the giant dinosaurs were covered with thick skins only; later on, they were to be protected by very thick scales that resembled armor.

Finally, another resident of the Triassic landscape was the *Cynognathus* **g,** a reptile from which the first mammalian forms evolved. In fact, the paleontologists who have studied the distribution of this animal in time have discovered that *Cynognathus* became extinct just as the first mammals appeared. Nevertheless, some very small mammals, poorly preserved and with highly uncertain and primitive forms, have also been found in Triassic rocks.



FLORA OF THE TRIASSIC PERIOD

the increasing specialization of plants



THE APPEARANCE OF SEEDS—This photograph shows two cross sections of *Araucaria* strobiles. The *Araucaria* was a conifer of the Mesozoic era. The strobiles, which were quite similar to modern pine cones, contained seeds —the plants' new means of reproduction. Reproduction by seeds was a noteworthy advance over reproduction by means of spores, which can be considered a carry-over from unicellular organisms. A spore, in fact, needs a particularly favorable environment near its point of release, whereas a seed, especially if it is encased in a fruit, is an autonomous system for conserving the reproductive faculties of the plant even during periods of adverse conditions.

In the course of evolution through a succession of geologic periods, the flora evolved much more slowly than the fauna. From the moment when plants invaded the land, their struggle for existence consisted chiefly of perfecting structural and physiological mechanisms that allowed a maximum exploitation of the substances contained in the air and the soil.

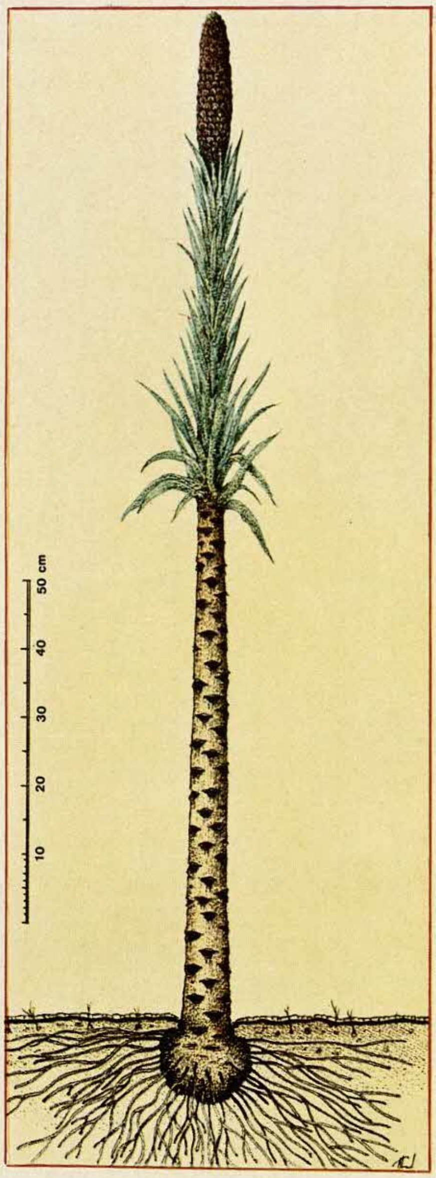
Plants, being fixed organisms, are much more subject than animals to climatic variations. Such variations may either help or hinder the development of a given species. Climatic variations that occurred in the preceding periods led to the establishment of characteristic floristic provinces with typical genera and species.

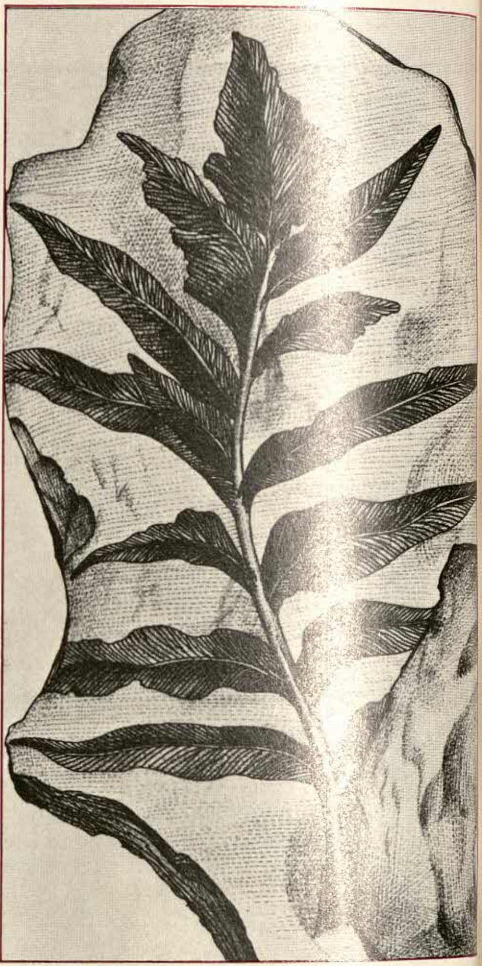
However, during the Triassic, the flora was quite homogeneous. It was mainly represented by the gymnosperms, which had first appeared during the Permian. Their greatest development was reached in the course of the Mesozoic era, and, above all, during the Triassic period. The angiosperms, which eventually came to dominate the landscape from the Tertiary down to the present times, had not yet appeared.

TRIASSIC CLIMATE AND FLORA

As mentioned previously, plants are extremely useful indicators of climatic conditions in given periods and places, especially when correlations can be established between fossil species and living species with known habitats. For the Triassic period, scientists have based their reconstruction of the flora on an examination of plant macrofossils. This examination has shown that the climate during the period reached a maximum drought level, especially in the central part of Europe and the western United States. Under these conditions, coniferous plants are better adapted and more resistant than other kinds of plants. Transpiration is reduced to a minimum by the needle-shaped leaves of conifers; furthermore, the epidermis of the needles is impregnated with resinous sub-

SPECIALIZATION FOR DESERT LIFE—A very interesting characteristic of Triassic flora is their specialization. Even though the plants already had well-developed leaves, they were capable of adapting to the climate in much the same way as modern plants. For example, in a desert climate, Triassic plants took the form of succulents; an example was the giant *Pleuromeia*, whose shape and characteristics are reminiscent of a cactus. This plant had a very graceful shape and a well-developed root system; the upper half of its trunk was covered with appendages that served to increase its external surface area.

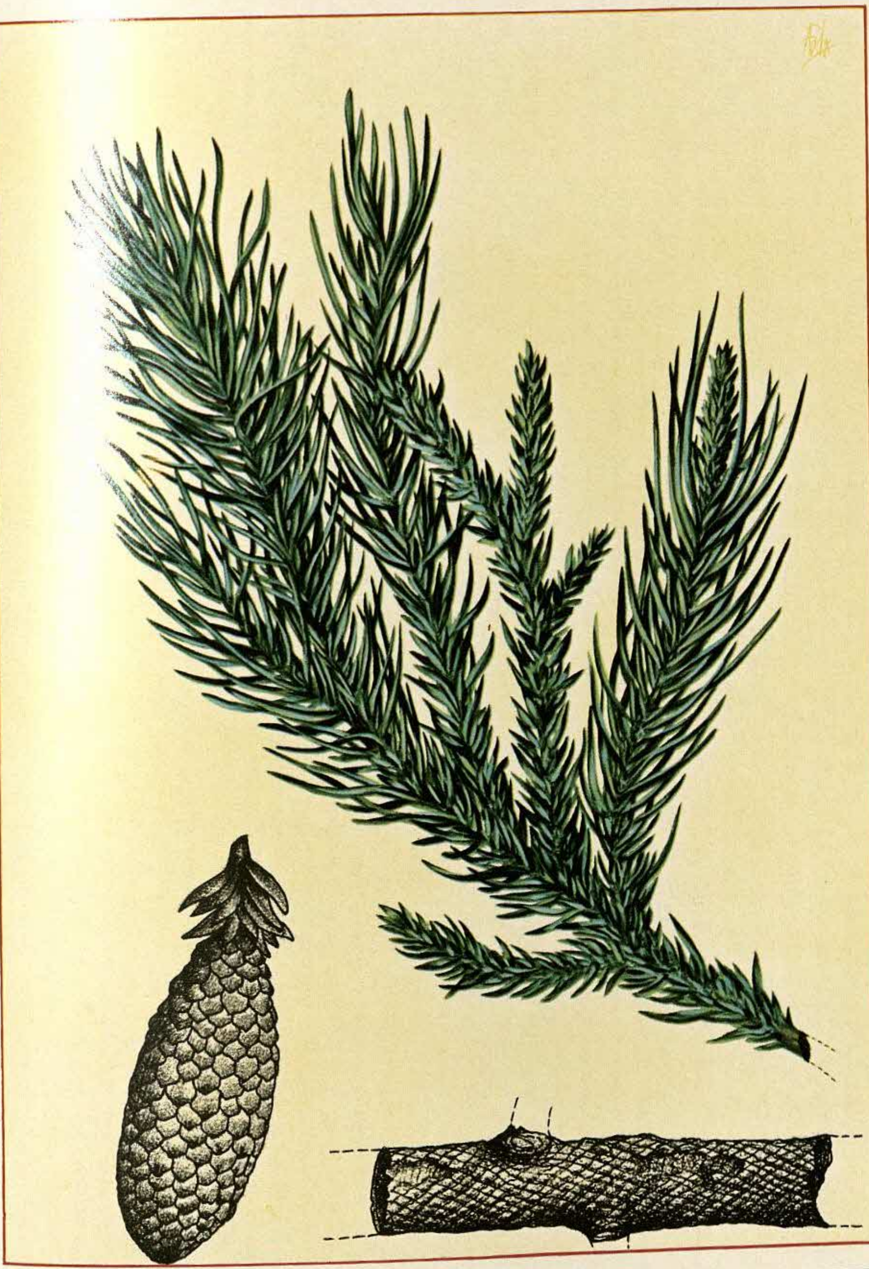




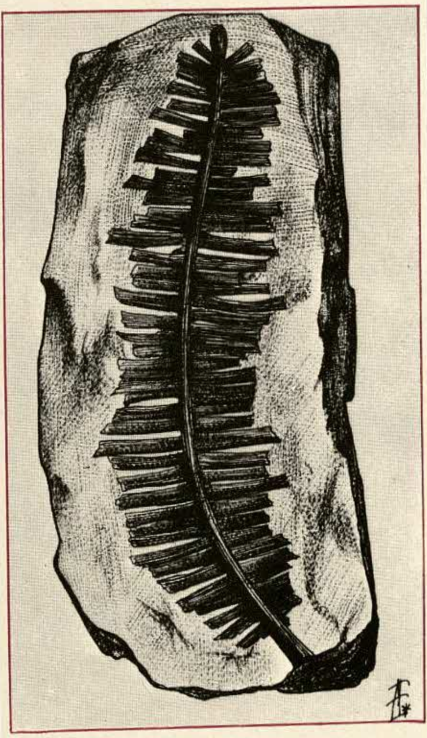
LEAVES IN DAMP CLIMATES—In places where the climate was damp, plants with highly developed leaf systems thrived, and in many cases they were already well differentiated.

The illustration shows the leaves of a small branch of *Thinnfeldia decurrens.* The specimen was found in Triassic rocks of the African continent. However, this plant is known to have been distributed not only throughout southern Africa, but also in all the areas that constituted the ancient continent of Gondwanaland—that is, the areas that presently comprise all the southern lands. The presence of a plant that has wide leaves or that can be recognized as a hydrophile is sufficient to indicate a damp climate; but the absence of such a plant is not sufficient to prove the existence of a dry climate. Today, however, on the basis of available data concerning sedimentary rocks, it is possible to say that the climate of central Europe was dry during the Triassic period.

THE CONIFERS—The composition of the trunk, the branch, and the cone of *Voltzia heterophylla*, which come from rocks of the Lower Triassic in Germany, call to mind structures of a present-day conifer. In fact, the coniferous forests of the present-day taiga undoubtedly resemble rather closely the forests that existed in primitive times before the flowering plants had appeared. The structure and physiological organization of the conifers enabled these plants to withstand the climatic conditions of the Triassic period, and their exceptional resistance has permitted them to survive to the present day. The needle-like leaves are well adapted for water conservation, and the branch structure is the best suited for withstanding the weight of a heavy snowfall. The appearance of the conifers was indeed an exceptional event in the evolution of the flora.



THE LEAVES OF A CYCAD—This cycad, the *Pterophyllum jaegeri*, has leaves consisting of appendages inserted perpendicularly into the trunk; it resembles a single large papyrus leaf that has been cut and trimmed. The characteristics of the leaves vary from type to type.



stances that further reduce the loss of water. Scientists have deduced, therefore, that the central part of Europe was covered by a huge coniferous forest that was not very different from the one covering that part of the Earth today.

It must be remembered that forests react readily to climatic changes; such changes can lead to radical changes in the flora. In regions that were subjected to glaciation, the flora probably varied at least a dozen times.

The vegetation in late Triassic time was characterized by a greater variety of plants distributed over many parts of the world. There were marked differences in character between the floras on opposite sides of the Equator; the Southern Hemisphere was like savannas are today.

THE JURASSIC PERIOD | the peak of dinosaur development

DINOSAUR EGGS—The discovery of fossilized dinosaur eggs testifies to the existence of a great number of these reptiles, because materials such as eggs are very rarely preserved. The size of dinosaur eggs varied considerably. Some with a diameter of 30 cm (about 12 in.) have been recovered in a state of perfect preservation. The casts of eggs shown in this photograph are about 20 cm (about 8 in.) long.

The name of this geological period is derived from the Jura Mountains, located in the center of continental Europe, in which the formations of this period are widely distributed.

The Jurassic, which followed the Triassic period, began about 180 million years ago and had a total duration of about 50 million years. During the course of this period a highly differentiated and very rich fauna evolved. This evolution depended mostly on the adaptation of living organisms to periodic changes in climatic and ecological conditions, and it led to an extensive specialization of the flora and fauna. Discoveries of fossils reflecting this specialization have made possible a very precise stratigraphical differentiation of the various formations.

The Jurassic period witnessed especially important events concerning both the geographic changes in the Earth and the development of life. Orogenic activity was reduced, although some folding occurred on a few continents. Near the end of the period an important orogenic phenomenon led to the formation of the Sierra Nevada mountains and the Coast Ranges. The phenomenon persisted after the end of the period and was completed during the Cretaceous period. As a consequence of these events magmatic movements led to the formation of many plutons. Once formed, plutons remain buried until the agents of erosion wear away the overlying rocks to reveal them. Practically speaking, these orogenic phenomena were the last to occur in those geological eras that may be described as ancient. From the Precambrian time on, orogeny and the movement of the continents more than once changed the face of the Earth, but hardly anything in present-day morphology is reminiscent of these ancient upheavals; to reconstruct them on the sole basis of the scanty, existing evidence has often been extremely difficult. During the Mesozoic era, on the other hand, some changes directly influencing the conformation of the Earth today began to occur. For example, coral formations began to accumulate in the region later occupied by the Alps. During the Jurassic period and the Cretaceous period that followed it, these formations usually remained below sea level and emerged only occasionally. In addition, the movements of the European and African continental masses began—movements that later determined the orogenesis of the Alps during the Tertiary period. The emerged lands during the Jurassic were still joined into only two continents, the North Atlantic one and the southern one, Gondwanaland; but during the following periods the Earth began to take on its present-day appearance.

RAPID EVOLUTION IN THE ANIMAL KINGDOM

The Jurassic was the period when dinosaurs reached the height of their development. Reptiles were present in every environment and were differentiated into many species—aquatic, aerial, and terrestrial—that can be roughly divided into carnivorous and herbivorous varieties. During the Jurassic, the dinosaurs attained a great size and inhabited every part of the Earth where the climate was favorable. They were so characteristic of this time that the Mesozoic era has been designated the Era of the Reptiles.

The first flying vertebrates appeared during the Jurassic; in the preceding periods the only flying organisms were the insects, but they were not very numerous. Some specimens were small, while others, such as *Meganeura,* had wingspans of more than 0.5 m (about 20 in.). The vertebrates that first conquered the air were flying reptiles; this adaptation is another indication of the high degree of specialization reached by saurians.

Only at the end of the Jurassic did the first bird, *Archaeopteryx,* appear. This organism was the first animal known to have been covered with feathers. Its structure, even though already highly adapted for flight, was still very much like that of the reptiles, from which in fact it evolved. The appearance of the birds marked the beginning of the end for the flying reptiles, whose structure was certainly not ideally suited for flying.

The mammals began to appear during the Middle and Upper Jurassic. They were initially represented by small and primitive forms that continued through the Cretaceous period. Only after the Mesozoic era ended did mammalian evolution proceed rapidly.

The development of the mollusks was extremely rapid during the Jurassic as

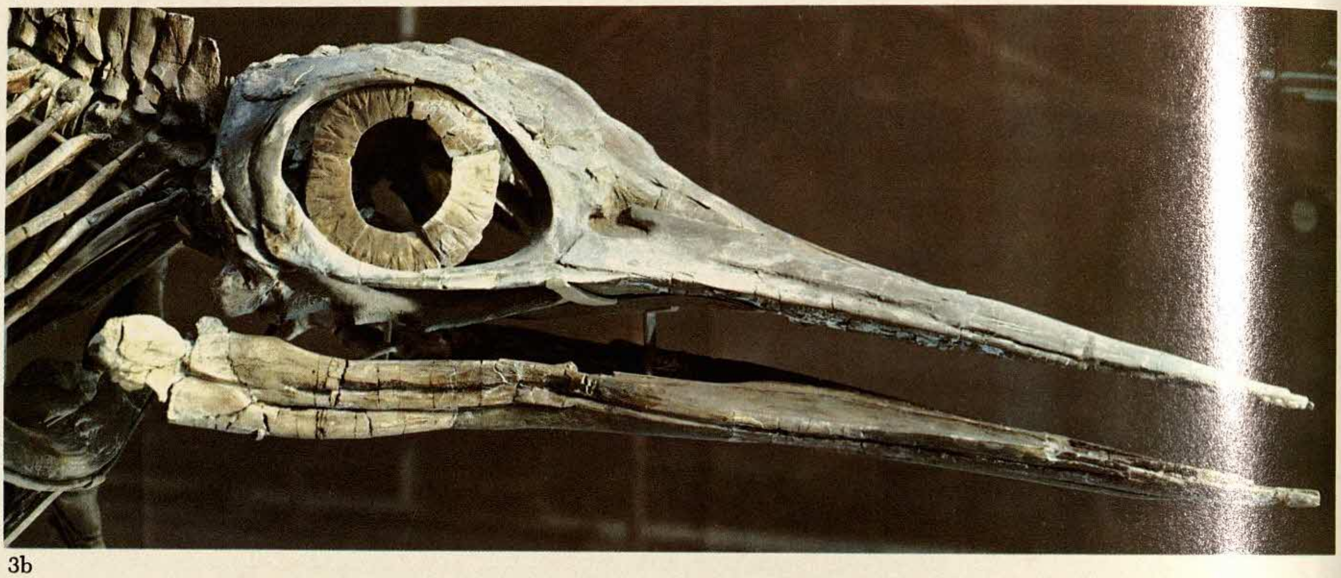
SUBDIVISIONS OF THE JURASSIC PERIOD—The Jurassic period has been subdivided into three epochs, which in turn have been subdivided into various ages. This subdivision has been made possible by the rapid evolution of the fauna during the period.

The names of the subdivisions shown in this chart are derived from European place names where the rock formations are fairly common. During the Jurassic period, many different marine transgressions and regressions occurred, and the sedimentary facies is often a marine one. On other continents where upheavals were few, the facies are prevalently continental. For this reason, fossils of giant dinosaurs are rarely found in Europe; such fossils are more common in other parts of the world.

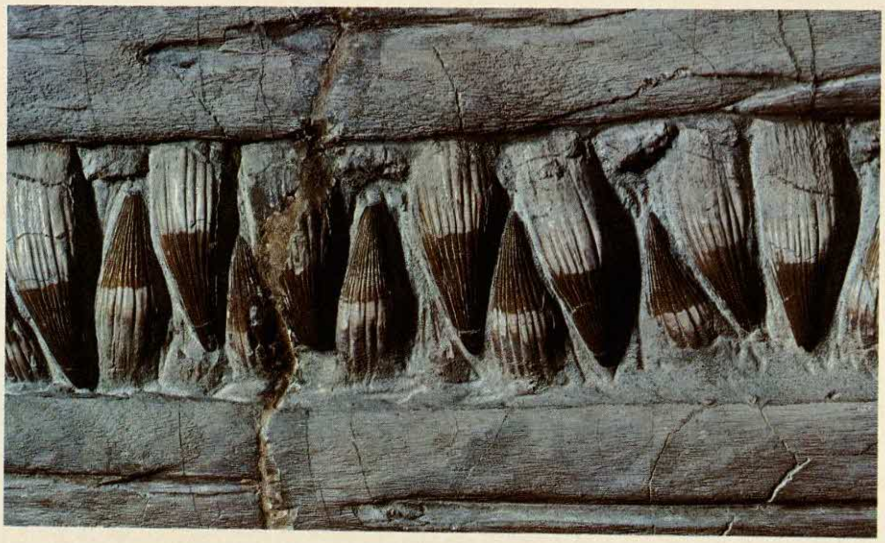
Scientists cannot give precise dates for the different epochs into which the Jurassic period has been divided, because the sedimentation rates in the various localities differed greatly. In other words, the length of an epoch is not even approximately measurable in terms of the thicknesses of the corresponding strata.

UPPER JURASSIC (MALM)	**Purbeckian**
	Portlandian
	Kimmeridgian
	Oxfordian
MIDDLE JURASSIC (DOGGER)	**Callovian**
	Batonian
	Bajocian
LOWER JURASSIC (LIAS)	**Toarcian**
	Pliensbachian
	Sinemurian
	Hettangian

3a



3b



TWO GENERA OF ICHTHYOSAURS—The skull of an aquatic reptile, *Ophthalmosaurus icenicus,* is shown in Illustration 3a. This animal grew to a length of 4 m (about [illegible] ft), but its body was relatively squat. The head was characterized by an exceptional development of the eye. The sclerotic bone was particularly large, and it gradually became larger as the animal matured.

The teeth of *Ichthyosaurus communis,* while always rather strong and robust, were not always identical, and they often varied considerably from one individual to another. Illustration 3b shows the detail of the dentition of one specimen.

far as both species and fauna associations are concerned; this fact makes it possible for stratigraphers to subdivide the levels of the Jurassic with extreme accuracy. The associations of organisms, both marine and subaerial, are also used as the basis for reconstructing the climates of the period.

The Jurassic, in short, was an important period of transition toward the modern era of life.

JURASSIC MARKS ON NORTH AMERICA

The marine Jurassic deposits on United States territory were from the Pacific and Arctic oceans and the Gulf of Mexico. The Arctic invasion reached as far south as Colorado and Utah late in Jurassic time. The Gulf invasion, which reached as far north as Arkansas, did not begin until late in the period. Vigorous vulcanism, some of which was submarine, accompanied the marine sedimentation in the West. The Arctic embayment was long and narrow. During the next period, it developed into a new geosyncline that had the same destiny as all subsiding troughs with excessively thick sediments; it was crushed and contorted into a mountain system—the Rocky Mountains. Much Jurassic nonmarine deposition also took place in what is now the western states, where thick dune sand dovetailed with marine beds.

Orogeny, which deformed and metamorphosed the thick western sediments toward the end of the Jurassic period, was accompanied by enormous granitic intrusions. The California mother lode and the Nevada Comstock lode date from this igneous activity. Modern stream waste from erosion of the mother lode gave California the gold rush of 1849.

Nonmarine Jurassic deposits in western North America have yielded enormous skeletons of dinosaurs. The first mammals appeared; and, small but agile, they managed to survive among the dinosaurs in the vicinity of Wyoming.

THE GEOLOGY OF THE JURASSIC PERIOD

changes in the lands and seas

The Jurassic period extended from about 180 million years ago to about 130 million years ago. This means that the geological changes of that period are relatively recent, insofar as geologic time is concerned. One fact stands out clearly: although these phenomena had direct influence on present-day terrestrial morphology, the Earth during the Jurassic had an appearance quite different from that of today. The continents had not yet acquired their present-day shapes or configurations, and they had probably not reached their present-day positions.

The great land areas of the Earth were joined together to form two huge continental masses, the North Atlantic Continent in the Northern Hemisphere, and Gondwanaland in the Southern Hemisphere. The continent of Gondwanaland seems to have been divided into two blocks that continued to drift apart. One of these blocks encompassed present-day Africa and South America; the other, Australia, Madagascar, and the Indian peninsula. The edges of all the landmasses underwent continual change during the 50-million-year span of the Jurassic period, and geologists have a fairly detailed knowledge of these changes.

MARINE TRANSGRESSIONS AND REGRESSIONS

The history of marine transgressions and regressions has been fully recorded. Although limitations of space prohibit discussion of all these changes, some of the more important ones will be mentioned.

The Tethys Sea, connecting the present-day Mediterranean with the seas of Asia, underwent many changes during the Jurassic period. In the early part of the period, for example, it advanced and expanded to cover the west central part of Asia.

During this time, a transgression also covered parts of western Europe from Spain to western Germany. As this water retreated, a large lake was formed. Land emerged from the lake in several places, and important continental deposits were formed. These deposits, rich in fossils, have permitted paleontologists to reconstruct in great detail the fauna of Europe.

North Africa was also covered by a transgressing sea during the early part of the Jurassic, and Arabia was intersected by a sea that formed a gulf associated with the Tethys.

During the middle part of the Jurassic period, the Tethys transgressed land in the north and in regions adjacent to the Mediterranean basin. In addition, a sea extending from the south connected with the Tethys to separate a large tract of land in West Africa from the African continent proper. Still later, the Tethys and other seas regressed slowly, permitting the re-emergence of Spain, parts of North Africa, and certain lands in the west. However, the Tethys continued to extend southward to join an arm of the Red Sea; the latter extended on to the west of the Ural Mountain chain. The middle part of the Jurassic was also marked by an extension of the Alpine geosyncline into southern Russia.

Late in the Jurassic, the Tethys reinvaded some of the land that it had abandoned earlier. At this time, the Tethys was connected with the Indian Ocean by a body of water that extended through the region north of the Himalayas. Although the seas were regressing from Africa and Arabia, they were transgressing in the areas of the Far East.

In the Western Hemisphere, Alaska was inundated by a transgressing sea during the early part of the Jurassic. In fact, for almost the entire period, the west coast of North America, from Alaska to California, was submerged. This region has been afflicted by many marine transgressions as well as by violent geologic phenomena, such as earthquakes and volcanic eruptions. During the Middle and Upper Jurassic, unusually explosive volcanic activity marked the region.

During most of the Jurassic, North America was divided in a north-south direction. A narrow strip of land separated the west coast sea from another shallow sea that had invaded the region now occupied by the Rocky Mountains. This sea disappeared prior to the end of the period, but sedimentary deposits of marine origin bear testimony to its existence.

In the south, modest transgressions occurred along the Gulf of Mexico. Shallow seas originating in the Gulf invaded parts of Mexico and western Texas, leaving fossiliferous marine deposits to attest to their incursions. In all probability, other land regions adjacent to the Gulf were also invaded periodically.

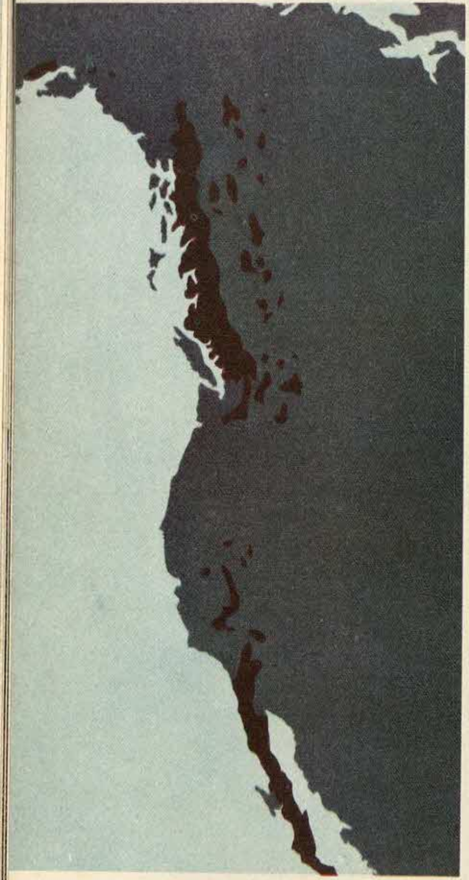
No marine transgressions occurred along the east coast of North America; in fact, the sea had probably regressed somewhat here so that the coastline lay somewhat east of its present position. Probably the entire eastern half of North America was undergoing extensive erosion during the Jurassic Period.

OROGENIC AND IGNEOUS ACTIVITY

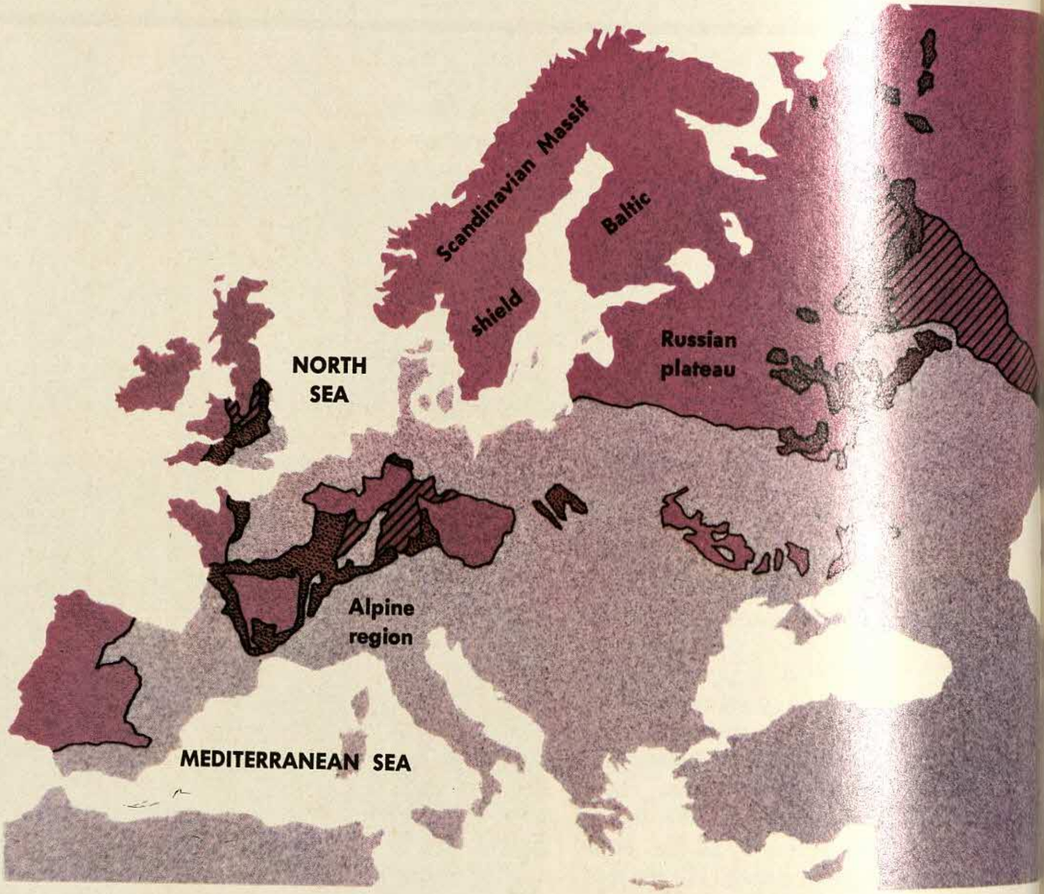
By and large, the Jurassic was not distinguished as a period of great mountain building. However, the early part of the period was marked by the Nevadan orogenesis, the phenomenon that produced the Sierra Nevada range of North America. About the same time, or perhaps a little later, igneous rocks of enormous dimensions were intruded along the western coast of North America. Some of these rocks, known as batholiths, have been exposed by prolonged erosion; part of one of these batholiths may be observed today in Yosemite National Park in California.

Intrusive and volcanic phenomena occurred throughout the entire length of the west coasts of North and South America—from Alaska, through California and the Andean region, to Cape Horn. The

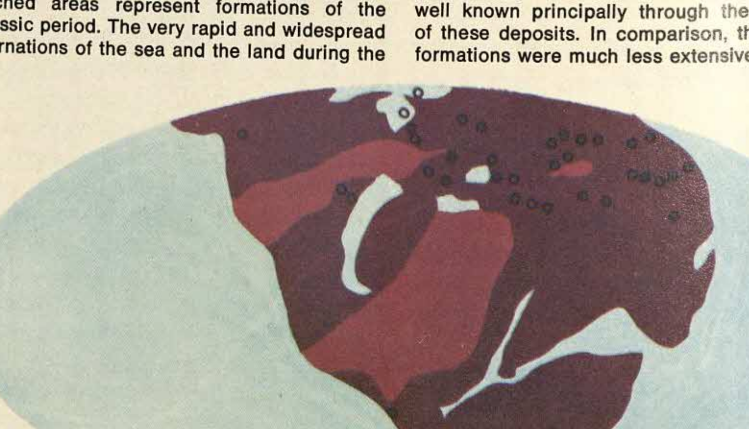
Cordilleran geosynclines, which extended southward through Mexico and Central America, and the Chilean geosyncline became seas from which rose low mountain chains studded with volcanoes. However, the great tectonic movements that formed the Rocky Mountain and Andes chains did not begin until late in the Cretaceous period of the Mesozoic era.



TESTIMONY OF OROGENESIS—On the whole, the Jurassic period was a period of relative orogenic calm. However, the Sierra Nevada Mountains of North America were formed during this period. Moreover, numerous batholiths were formed in the western part of North America during the Jurassic; they are indicated in red on this map. Although these batholiths are of Jurassic age, they did not appear during that period; they appeared much later, after the overlying rocks had been eroded. Batholiths of Jurassic age have been uncovered in mountain ranges in the Balkans. Magmatic or igneous phenomena also occurred in Europe.



JURASSIC OUTCROPS IN EUROPE—The dotted areas on this map represent formations deposited during the Jurassic period; the hatched areas represent formations of the Triassic period. The very rapid and widespread alternations of the sea and the land during the Jurassic led to the formation of vast sedimentary deposits that later came to the surface. The geology and the fauna of the Jurassic are well known principally through the existence of these deposits. In comparison, the Triassic formations were much less extensive.



POLES AND CONTINENTS—During the Jurassic period neither the poles nor the continents were in their present positions. Their supposed positions are shown in this map; the poles are marked by arrows and the equator with the dark line. The continents may have been joined together in one huge sialic reef on a part of which (the pink-colored area in the illustration) the climatic conditions were of the desert type. The circles, on the other hand, mark off the areas containing coal formations, sure indications of warm and damp climatic conditions.

FAUNA OF THE JURASSIC PERIOD

some characteristic animal forms

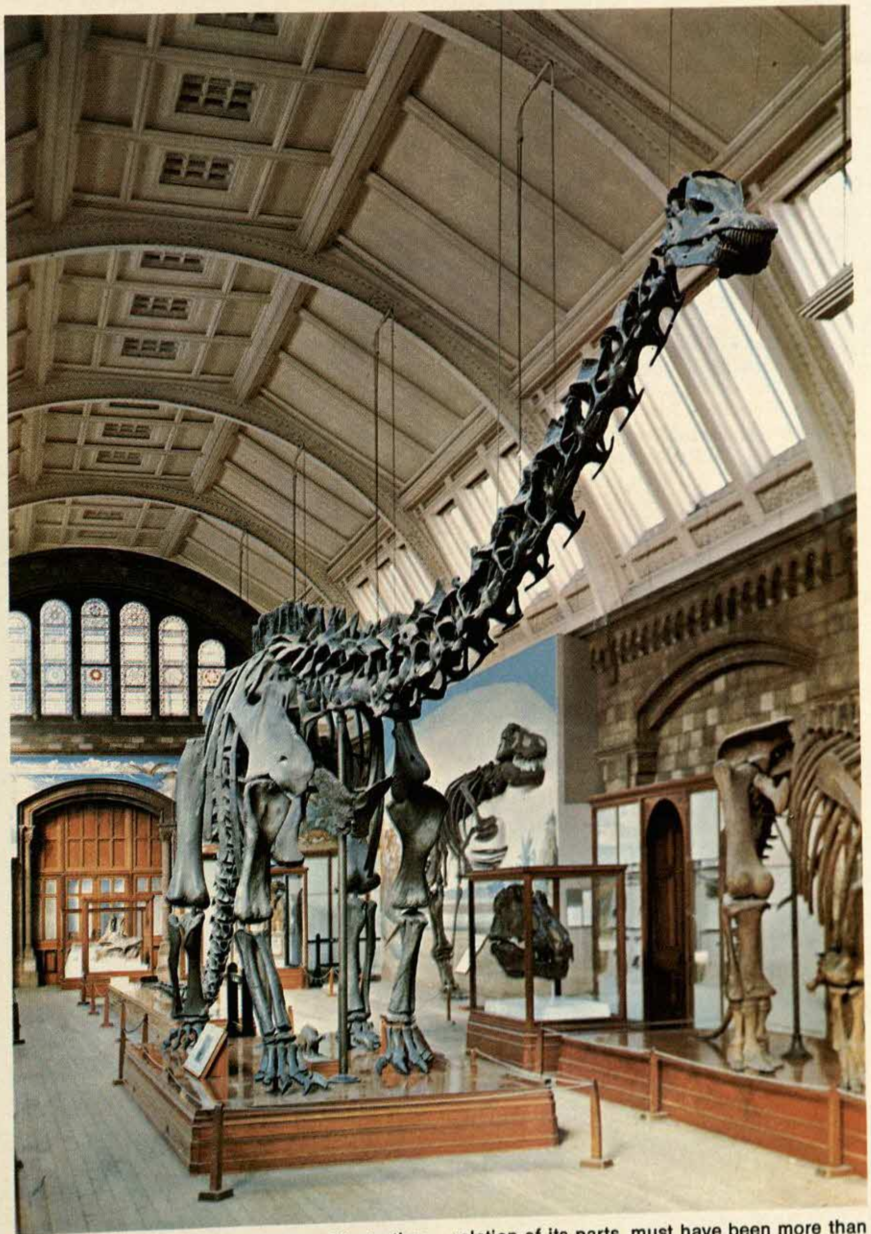
In spite of the fact that the Jurassic period was a period of transition between the Triassic and the Cretaceous periods, its fauna had few intermediate characteristics; instead, Jurassic fauna had well-defined features, which distinguish these animals clearly from the fauna of the preceding period.

In the Triassic fauna, all those phenomena that underlie an evolutionary process were evident. In fact, by the end of the Triassic period, many representatives of the animal classes, from the minute unicellular organisms to the still small and imperfect mammals, were already present. However, during the Jurassic a great number of new species were created in these classes, due in part to the appearance of new adaptations and in part to the flourishing of numerous new specimens.

One of the most interesting characteristics of the Jurassic period, therefore, was the great variety of aquatic and terrestrial animals. Each environment had its own predominant species, but numerous similar varieties (which evolved from the same stock) existed side by side with the dominant species. This fact indicates that a great diversification of species occurred. A thorough examination of all the species living during the Jurassic would reveal an enormous variety of forms; only the most significant forms are discussed here.

MANY DOMINATIONS

To say that the dinosaurs dominated the Earth is only a partial truth. The dinosaurs were certainly the largest terrestrial animals and the most formidable hunters, but they coexisted with certain other kinds of large animals. Besides the various types of dinosaurs, the continental reptiles were well represented by numerous forms of Chelonia (turtles). Of the marine reptiles, the most important were without doubt the Ichthyosauria and Plesiosauria. Flying animals, including both reptiles and birds, became definitely established during the period, and some small mammals were in evidence.



THE HERBIVOROUS DINOSAURS—Illustration 1 shows a reconstructed skeleton of the enormous *Diplodocus carnegii*, a Jurassic dinosaur that often grew to a length of nearly 30 m (about 98 ft). Excluding the tail, which was very thin at the end, the dimensions of this animal were truly exceptional. Its weight, estimated on the basis of the principle of the correlation of its parts, must have been more than ten tons. The limb bones were extremely robust. In contrast with its frightening appearance, the animal was exclusively herbivorous, as can be deduced from its teeth. The small size of the teeth suggests that *Diplodocus* fed on soft, lush aquatic vegetation that could be eaten with little effort.

The marine environments of Jurassic times contained many species of lower animals, including radiolarians, echinoderms, and mollusks. In the oceans, Foraminifera had become so plentiful and characteristic that they are highly useful as zone markers in the Jurassic and Cretaceous periods. Sponge spicules and skeletons also are prominent in deposits of those periods. In the late Jurassic, sponges were important reef builders in central Europe. Among cephalopod mollusks, the belemnites flourished, the teuthoids increased considerably, and the first cuttlefishes made their appearance.

From this time on in geologic history, nautiloids were of little importance; the Jurassic forms are rare as fossils. On the other hand, ammonoids proliferated, with about 600 Jurassic genera, including many useful horizon markers.

Gastropods and pelecypods abounded in this period. Among the crustaceans, the first crablike forms appeared. Bryozoans, which had approached extinction by the end of the Paleozoic, had a revival. Although other brachiopods were unimportant, the *Terebratula* and *Rhynchonella* groups reached the peak of their development in the Jurassic. Crinoid

2

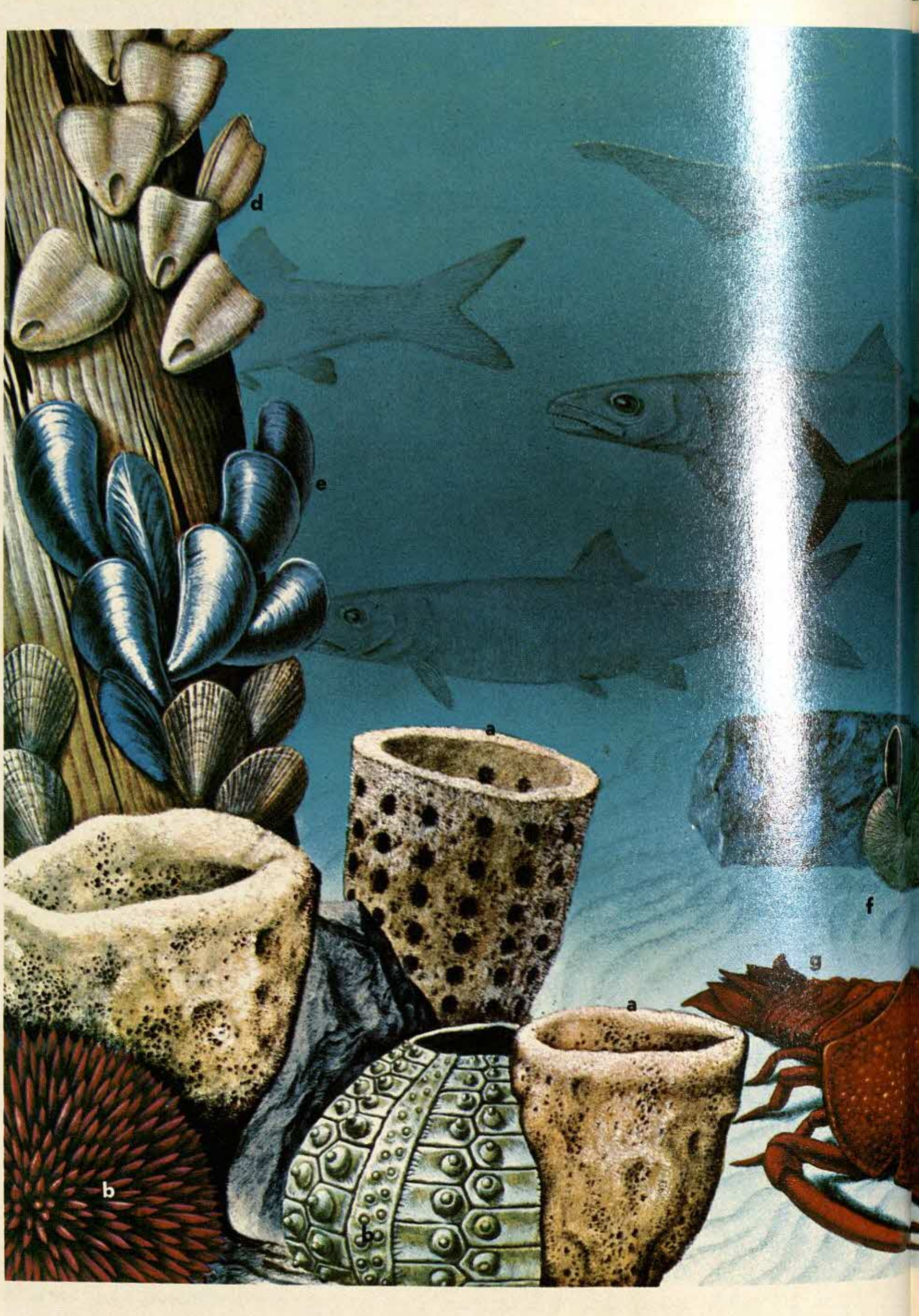
THE JURASSIC SEA—Because the reptiles have been excluded from this underwater scene, the illustration may resemble a seascape of the Triassic period. In this illustration are gathered together the most typical specimens of the three epochs into which the Jurassic has been subdivided.

The Jurassic seas contained abundant radiolarians (not shown because of their minute size). These protozoans, characteristic of deep waters, have been found in rocks of very ancient periods; the chemical composition of their skeletons made their fossilization possible.

The most striking characteristic of the Jurassic sea is, however, the great extension reached by the coral reefs, particularly during the Dogger Epoch (Middle Jurassic). Among the benthic animals were the siliceous sponges **a**, among which moved a few echinoids **b.** Some beautiful and graceful crinoids **c** were also present.

Brachiopods **d** and lamellibranchs **e** characterized the fauna of both the shore and pelagic zones. This fact is very important for the geologist because it permits him to make an immediate reconstruction of the environment in which a particular rock formed. The ammonites **f** were also present together with belemnites and nautiloids. From the stratigraphic point of view, the ammonites were perhaps the most important fauna in this period.

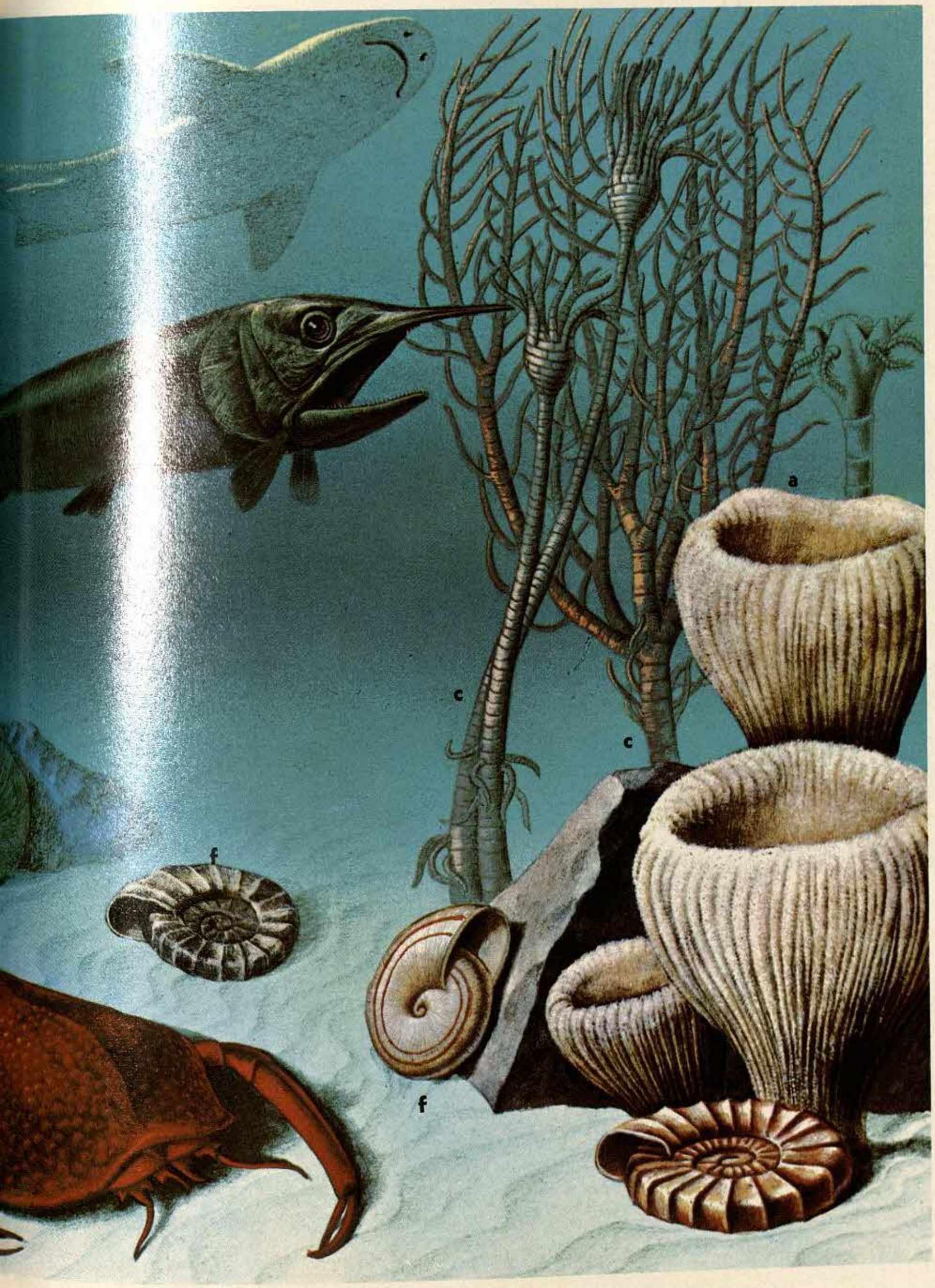
Also shown is a crustacean, *Eryon propinquus* **g,** which was about as large as a present-day shrimp, and some fish representing the selachians, teleosts, and ganoids.

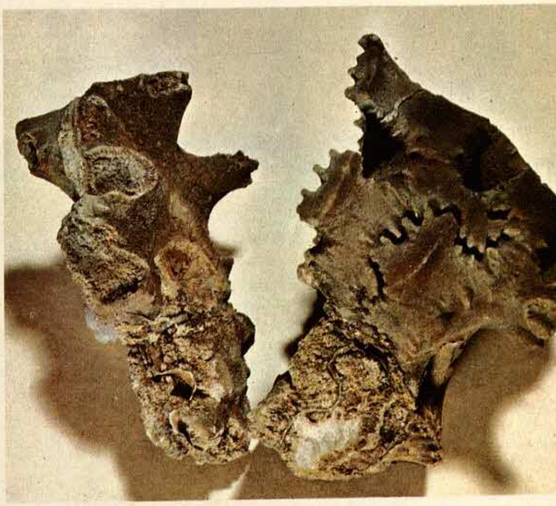


echinoderms were again common but not in the same abundance they reached in Paleozoic time; the continued expansion of the echinoid class was the most notable event among the echinoderms.

Fishes swarmed in the Jurassic seas. A number of shark families and a primitive skate branched off from the ancestral hybodonts. Small fishes, such as *Leptolepis,* attained the final major stage of ray-finned evolution in the form of primitive Teleostei.

The nature of Jurassic rock formations has permitted the perfect preservation of a large number of continental and marine fossils of various sizes.

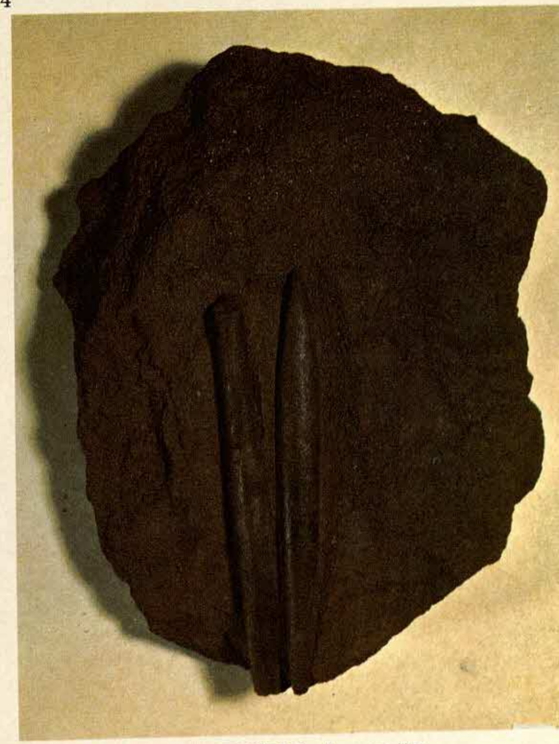




3

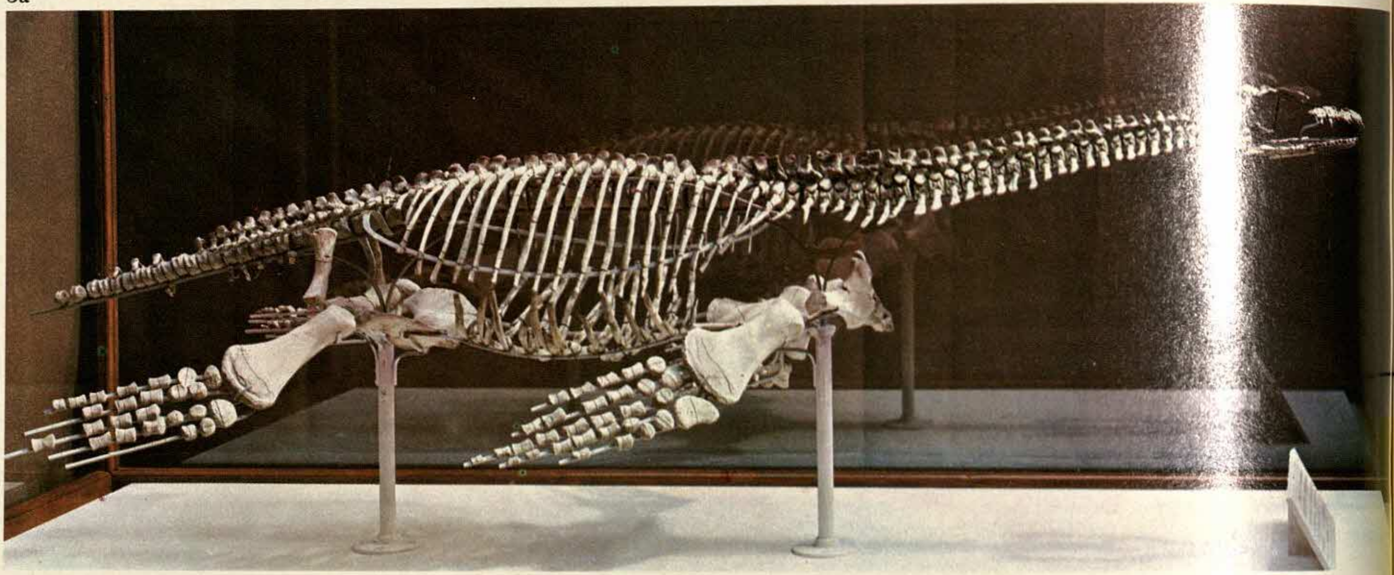
THE PERIOD OF THE AMMONITES—The ammonites reached their peak during the Jurassic period of the Mesozoic era. These cephalopods evolved rapidly, and their remains have been discovered so frequently that they can readily be used as index fossils in stratigraphic studies. One of their interesting features is the presence of suture lines on the shells. This photograph shows an *Arietites* of the Sinemurian Age (Lower Jurassic). The specimen has been opened along the suture line to show the complexity of the line.

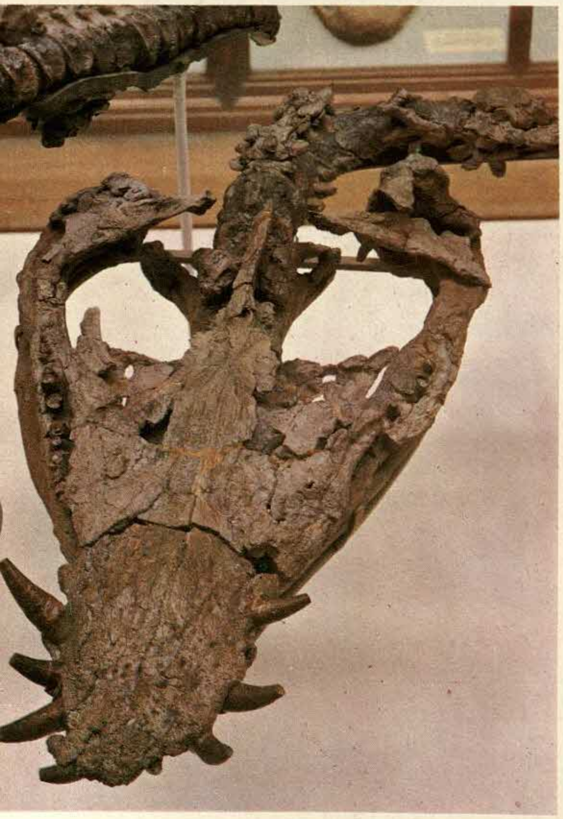
4



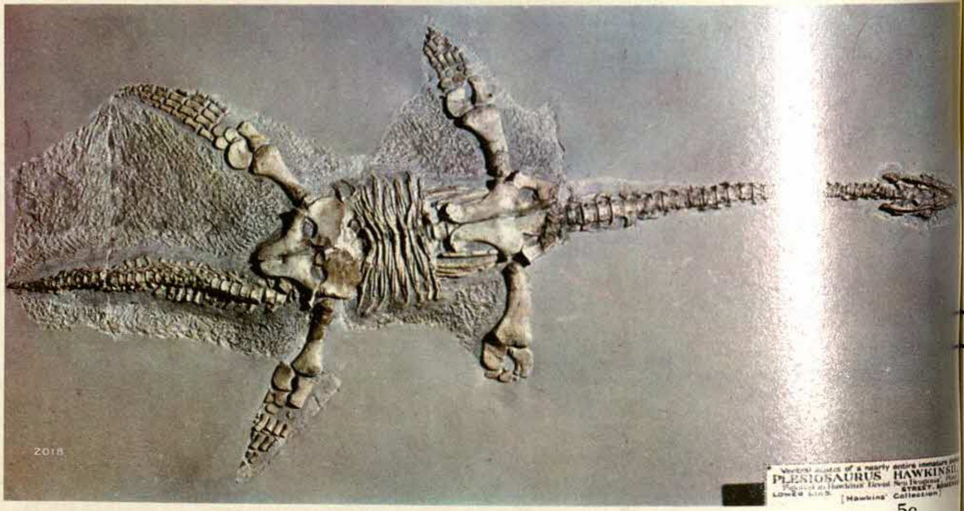
ROSTRA OF THE BELEMNITES—Among the fascinating fossil finds in Jurassic rocks are the rostra of the squidlike cephalopods known as belemnites. The robust calcite rostrum of a belemnite is typically cylindrical in shape with a long, pointed conical, or oval, tip.

5a





5b



5c

THE PLESIOSAURIA—The Plesiosauria was a large suborder of marine reptiles. Because of its very long vertebral column, a plesiosaur was once described as a snake encased in a tortoise shell. The shell joined the extremely small head to a short body ending in a rather long tail (Illustration 5a).

The skull of a plesiosaur (Illustration 5b) was short and rather thick. The teeth differed in shape and size from those of the ichthyosaurs, and the mandibles were shorter. The brains of these animals—and of all the reptiles in general—were never large; in some dinosaurs, for example, it has been noted that the dimensions of the brain were smaller than the diameter of the spinal cord. Therefore, the organs of sense were not very highly developed and the intelligence was of a relatively low order. This observation indicates that both the defense and the conservation of the species were entrusted exclusively to the animals' strength and enormous size.

The extremities of the limbs of a plesiosaur (Illustration 5c) were somewhat similar to those of an ichthyosaur; this is an example of the phenomenon of convergence. In both animals, of course, the limbs were used for locomotion and steering through the water.

HIGHER ANIMALS | reptiles, birds, and mammals of the Jurassic period

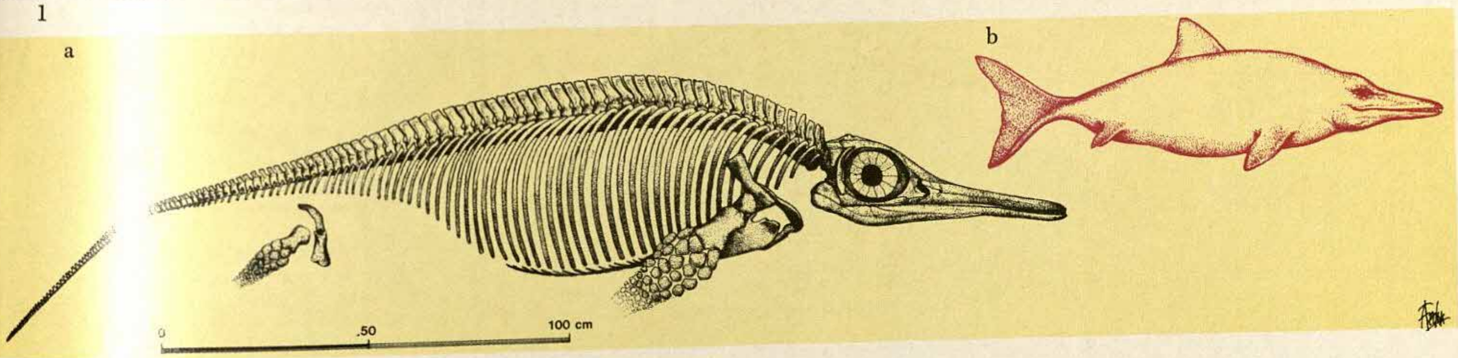
If the lower fauna of the Jurassic period was represented by an astonishing variety of species, the higher fauna, which had a predominantly subaerial life, was no less interesting. It, too, was very rich, and some animals with rather modern characteristics made their appearance in it for the first time.

Nevertheless, the Jurassic fauna remained prevalently archaic. This is demonstrated by the fact that the reptiles still dominated all other forms. Large numbers of them were present in all environments, and they existed in diverse shapes and sizes.

Although the mammals had already made their appearance, they had not yet acquired any particularly noteworthy characteristics; in size, they were universally small, many no larger than modern shrews and the largest probably approaching the size of a large rat. It was during the Mesozoic era, though, that the basic mammalian pattern was set.

Mammals arose from the Therapsida, an order of reptiles that became extinct early in the Jurassic period. During the course of their evolution, several lines of therapsid reptiles became increasingly mammal-like; and the group as a whole is popularly known as mammal-like reptiles. The Ictidosauria, later members of one suborder of therapsid reptiles, are so much like mammals that it is largely a matter of opinion whether they are, in fact, reptiles or mammals.

1

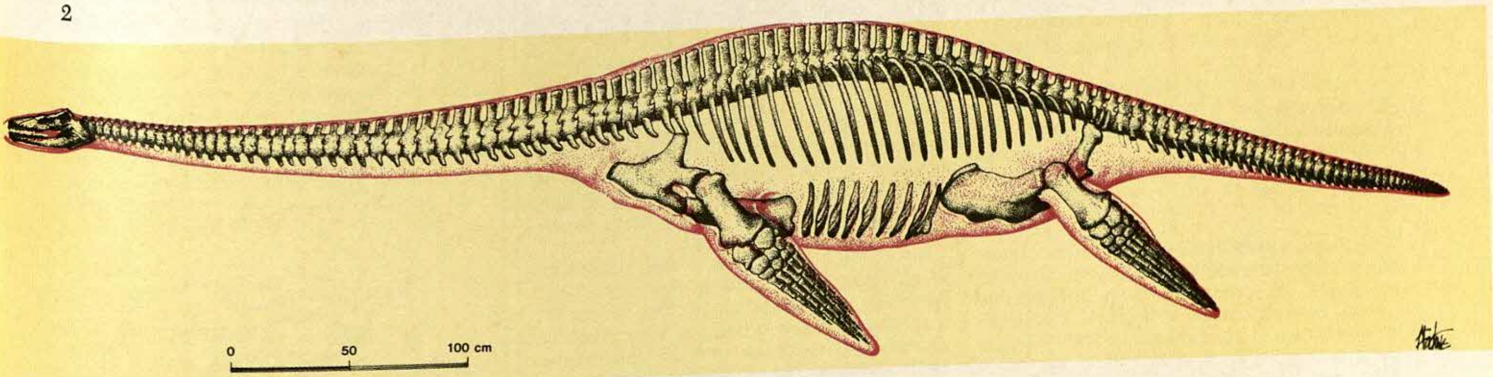


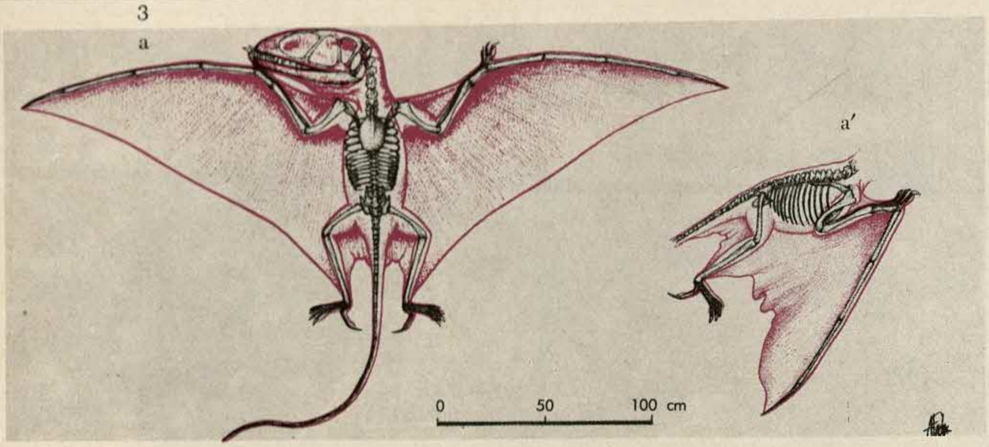
THE STRUCTURE OF THE ICHTHYOSAURS—During the Jurassic period the ichthyosaurs reached their maximum distribution; in the following period, the Cretaceous, only a few rare specimens of this group remained. The reconstruction of this skeleton of *Ophthalmosaurus icenicus* (Illustration 1a) provides a good idea of ichthyosaurian structure.

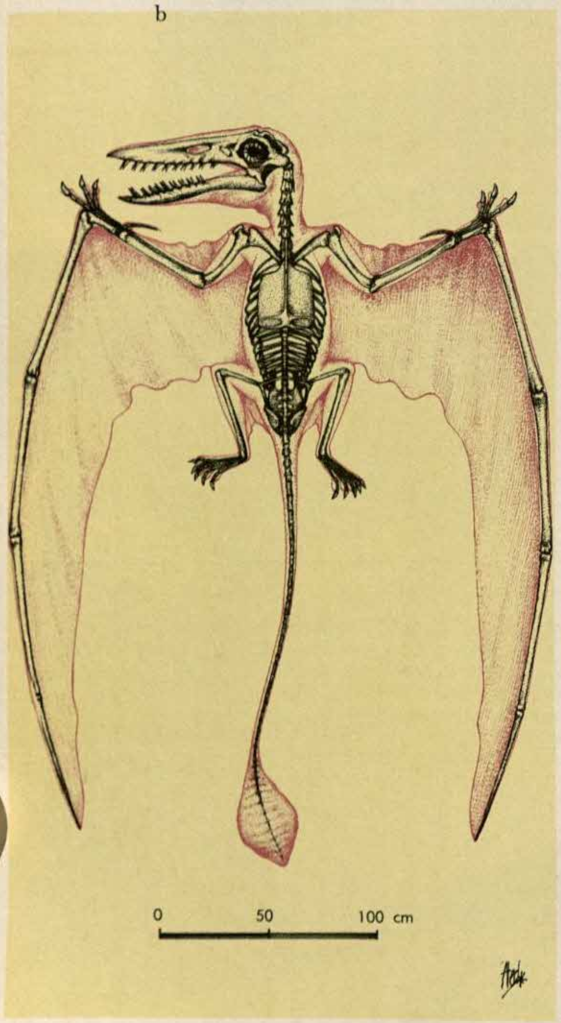
The *Ophthalmosaurus* of the Upper Jurassic, even though it was nearly 4 m (about 13 ft) long, had a very squat body. The animal had a thorax of great capacity and the extremities had been transformed into swimming fins. The long tail was bent downward to support the extremely large caudal fins.

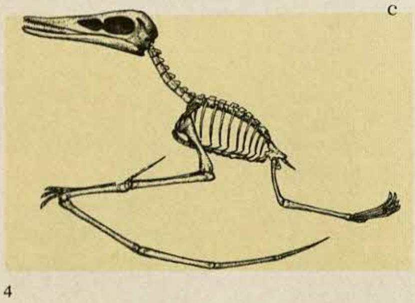
APPROACHING DEFINITIVE FORMS—Of a more harmonious shape, but perhaps more frightening appearance, was the plesiosaur. Among the numerous existing specimens, *Muraenosaurus seely* of the Oxfordian age (Upper Jurassic) has been illustrated. A comparison of the characteristics of this animal with those of the Cretaceous plesiosaurs is interesting. The latter increased in length considerably, and the thorax and abdomen moved farther back, thus improving the animal's hydrodynamic properties. *Muraenosaurus* had a length of about 6 m (about 20 ft); this length doubled in the Cretaceous, and then the Plesiosauria disappear. This means that the Jurassic plesiosaurs were still evolving and can be considered as intermediate forms. The skull was very small; the spinal column arched at the level of the thorax, but became straight in the later types. The thorax and limbs were quite suitable for swimming.

2









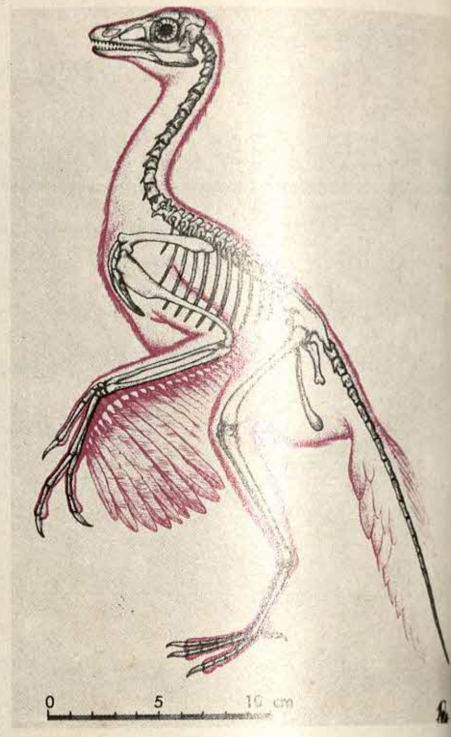
THE FLYING REPTILES—During the Jurassic period, the flying reptiles underwent rapid development. To solve the problem of flight, vertebrate animals needed a structure completely different from that required for swimming or walking. First, the animals had to develop a light, but strong, skeleton; the bones had to take on a complex structure and perhaps become hollow. Second, the animals needed to develop some kind of wing structure; the wings that were evolved by the reptiles consisted of a light, strong membrane derived from the skin.

Dimorphodon (Illustration 3a) was one of the first flying reptiles. It possessed strange characteristics, such as a very long whiplike tail (useless in flight), highly developed hind legs, a huge skull, and rather small wings supported by long fingers. In all the flying reptiles the main structure of the wing consisted of a short arm and a very long finger, which held the flapping membrane open (Illustration 3a′). This animal marked the earliest stage of evolution, and the flights of *Dimorphodon* were probably brief and rather clumsy.

A direct descendant of *Dimorphodon* was *Ramphorhynchus* (Illustration 3b), which was about the same size as its ancestor, but better adapted to flying, due to its thinner body, smaller and lighter skull, short hind legs, and long aerodynamic wings.

Little is known as yet about the life of the flying reptiles in the Jurassic. All that can be said is that they presumably lived around the edges of swamps and lakes and fed on terrestrial and aquatic animals. On the other hand, reconstruction is easier for the following period; in Cretaceous rocks scientists have discovered animal fossils containing food remains, thereby making it possible to establish that the habitual food of the flying reptiles was mostly aquatic animals.

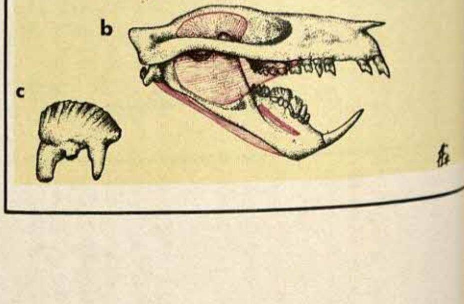
Of all the flying reptiles of the Jurassic, the most famous was certainly *Pterodactylus* (Illustration 3c). Without doubt, this animal was the most widespread and the most diversified animal of its kind; all told, 23 species have been identified. Some species were as small as a blackbird, while others were as large as a goose.

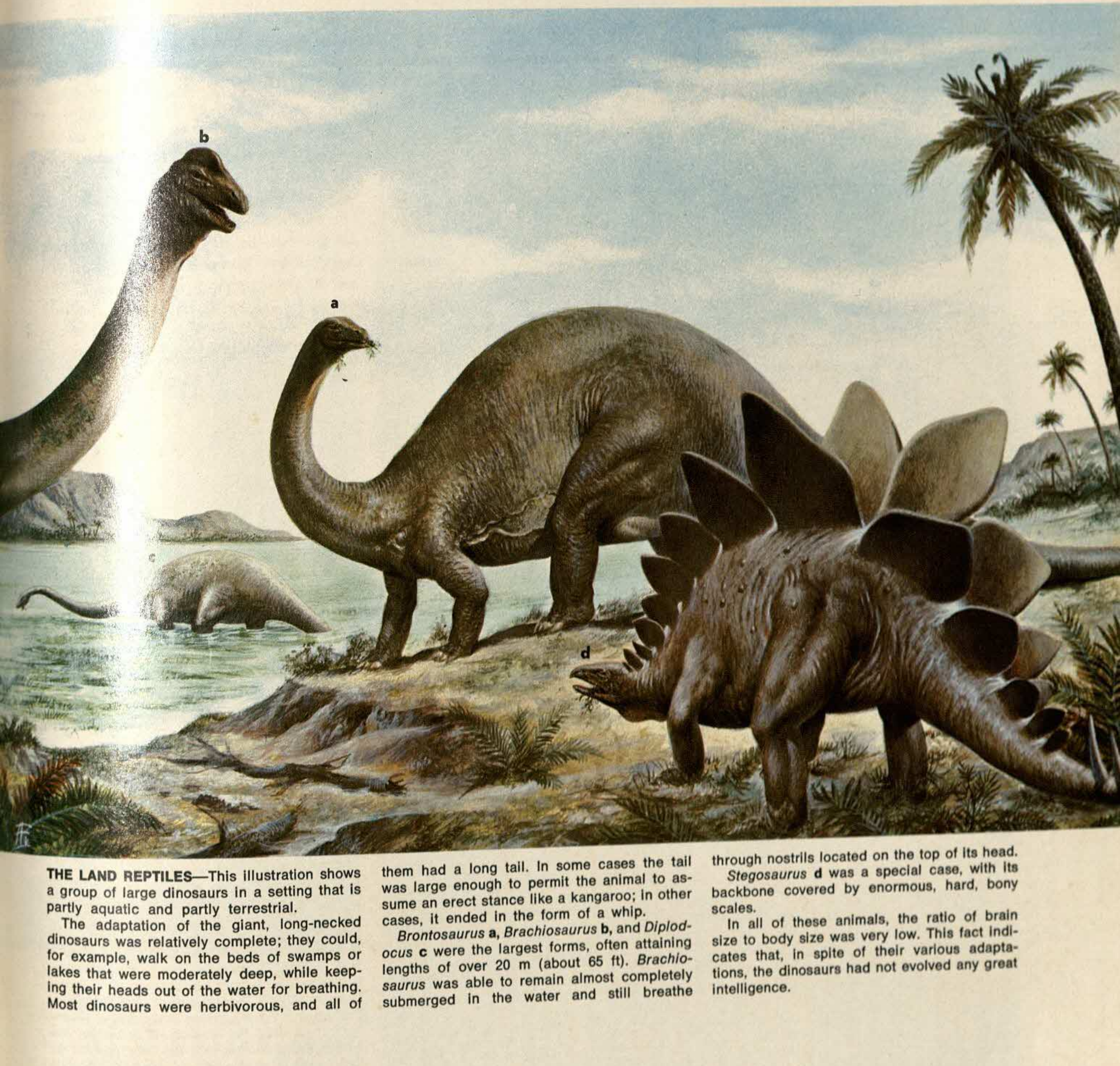


ARCHAEOPTERYX—This illustration shows the still archaic skeleton of the first bird. The tail of *Archaeopteryx* was provided with strong vertebrae, and the wings had a simple structure in which the bones were free rather than joined together in a single piece to support the feathers; furthermore, this bird had teeth quite similar to those of the reptiles, of which it was a direct descendant. Two specimens of this animal have been found. Although *Archaeopteryx* had a clearly primitive form, it was without doubt the forerunner of a new class of animals, the birds.

5

THE FIRST MAMMALS—The mammals made their appearance during the Jurassic. A few specimens have been found in many zones of the North Atlantic continent. These drawings depict the reconstruction of the head **a,** the skull **b,** and a premolar tooth **c**—all of *Ctenacodon* of the Jurassic.





THE LAND REPTILES—This illustration shows a group of large dinosaurs in a setting that is partly aquatic and partly terrestrial.

The adaptation of the giant, long-necked dinosaurs was relatively complete; they could, for example, walk on the beds of swamps or lakes that were moderately deep, while keeping their heads out of the water for breathing. Most dinosaurs were herbivorous, and all of them had a long tail. In some cases the tail was large enough to permit the animal to assume an erect stance like a kangaroo; in other cases, it ended in the form of a whip.

Brontosaurus **a**, *Brachiosaurus* **b**, and *Diplodocus* **c** were the largest forms, often attaining lengths of over 20 m (about 65 ft). *Brachiosaurus* was able to remain almost completely submerged in the water and still breathe through nostrils located on the top of its head.

Stegosaurus **d** was a special case, with its backbone covered by enormous, hard, bony scales.

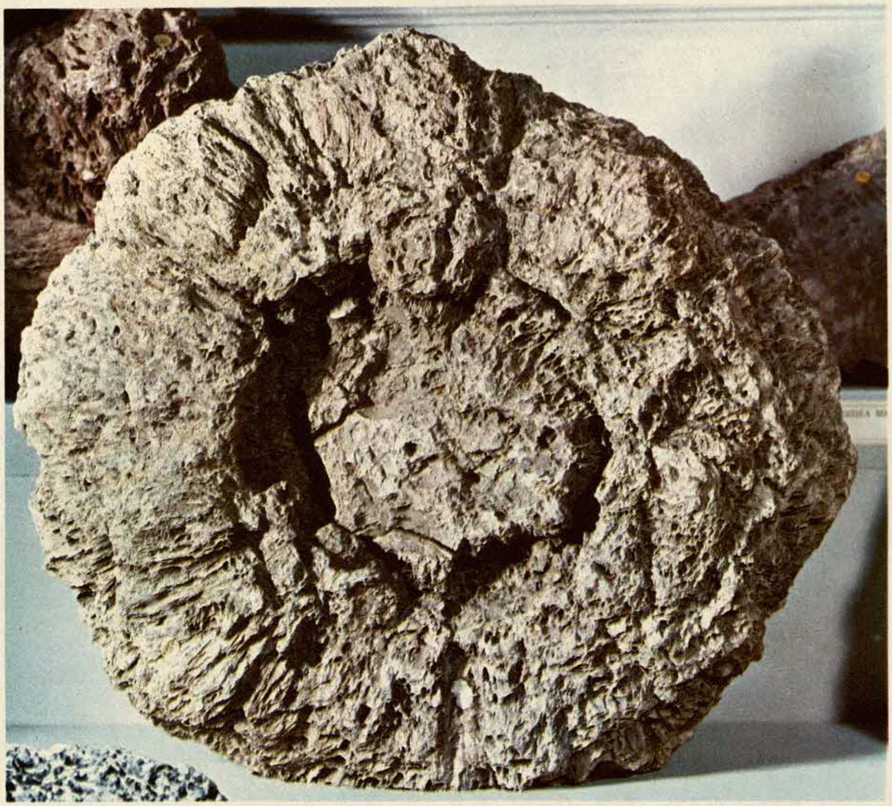
In all of these animals, the ratio of brain size to body size was very low. This fact indicates that, in spite of their various adaptations, the dinosaurs had not evolved any great intelligence.

FLORA OF THE JURASSIC PERIOD

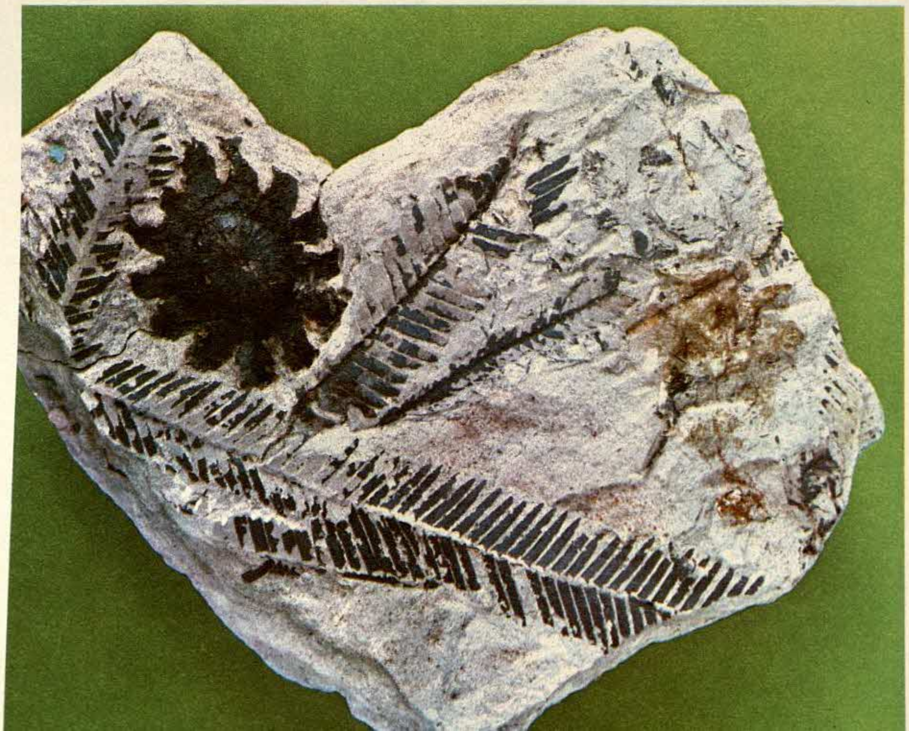
important plants of the period

THE NEW PLANTS—The Cycadales type of flora was expanding rapidly during the Jurassic, and scientists have discovered many fossil specimens of this order. From the fossils, a reconstruction of the plants has been carried out. Some Cycadales had features similar to present-day palms. The trunk evidently was not made of very compact wood; consequently, the fossil specimens (such as the one illustrated) have been altered considerably. Nevertheless, much of the sponginess evident in the photograph was not caused by decomposition, but was essentially part of the original structure.

1



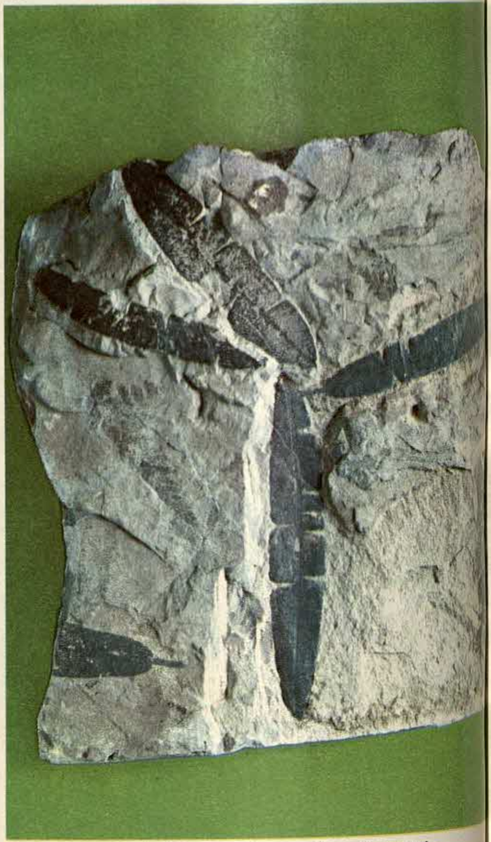
2a



The Jurassic period was extremely rich in both plant and animal life. Plant species were plentiful and diversified, and conditions were favorable for the fossilization of remains. Consequently, scientists have been provided in many cases with practically intact specimens of Jurassic plants.

A very important event took place in the evolution of plants during the Jurassic period: the angiosperms made their appearance. These flowering plants did not become preeminent until the Cretaceous, however, but paleobotanists know

2b



THE BENNETTITALES—The order Bennettitales was also widely represented by different species during the Jurassic. The fossils of these plants have enabled scientists to reconstruct not only the general structure of the plants, but also the delicate organs, such as the reproductive apparatus. These photographs show the fossil remains of two rather different types of Bennettitales, the *Williamsonia* (Illustration 2a) and the *Anomozamites* (Illustration 2b). The green color in the fossils is not due to the chlorophyll in the living leaf, but to an inorganic substance that by chance is also green.

the history of the angiosperms from their earliest origins because their remains (including pollen grains) have been remarkably well preserved by fossilization.

PREVALENCE OF THE GYMNOSPERMS

In the Triassic period, the conifers were the predominant plants, but during the Jurassic these plants had to share their position of importance with palmlike Cycadales and Bennettitales and the maidenhair Ginkgoales. It must be remembered, of course, that the first certain species of *Araucaria, Abies,* and *Cupressus* were present and have remained more or less unchanged down to the present time. The Cycadophytes may have been largely restricted to the more open savannas, though they doubtless mingled with ferns in the understory of the lowland forests.

In spite of the appearance of the angiosperms and the slight regression of the conifers, the Jurassic remained a period of gymnosperm domination. The seeds of gymnosperms have no protective coverings, and they are almost lacking in reserve substances; as a result, these seeds need especially favorable conditions in which to germinate. The seeds of angiosperms, on the other hand, have different characteristics and are much more independent of environmental conditions. It is easy to understand, therefore, that in the struggle for domination, the angiosperms would eventually emerge victorious. With the appearance of the angiosperms, the flora more nearly resembled modern flora than at any previous time. Still tens of millions of years would pass before the angiosperms attained their present state of evolution and distribution.

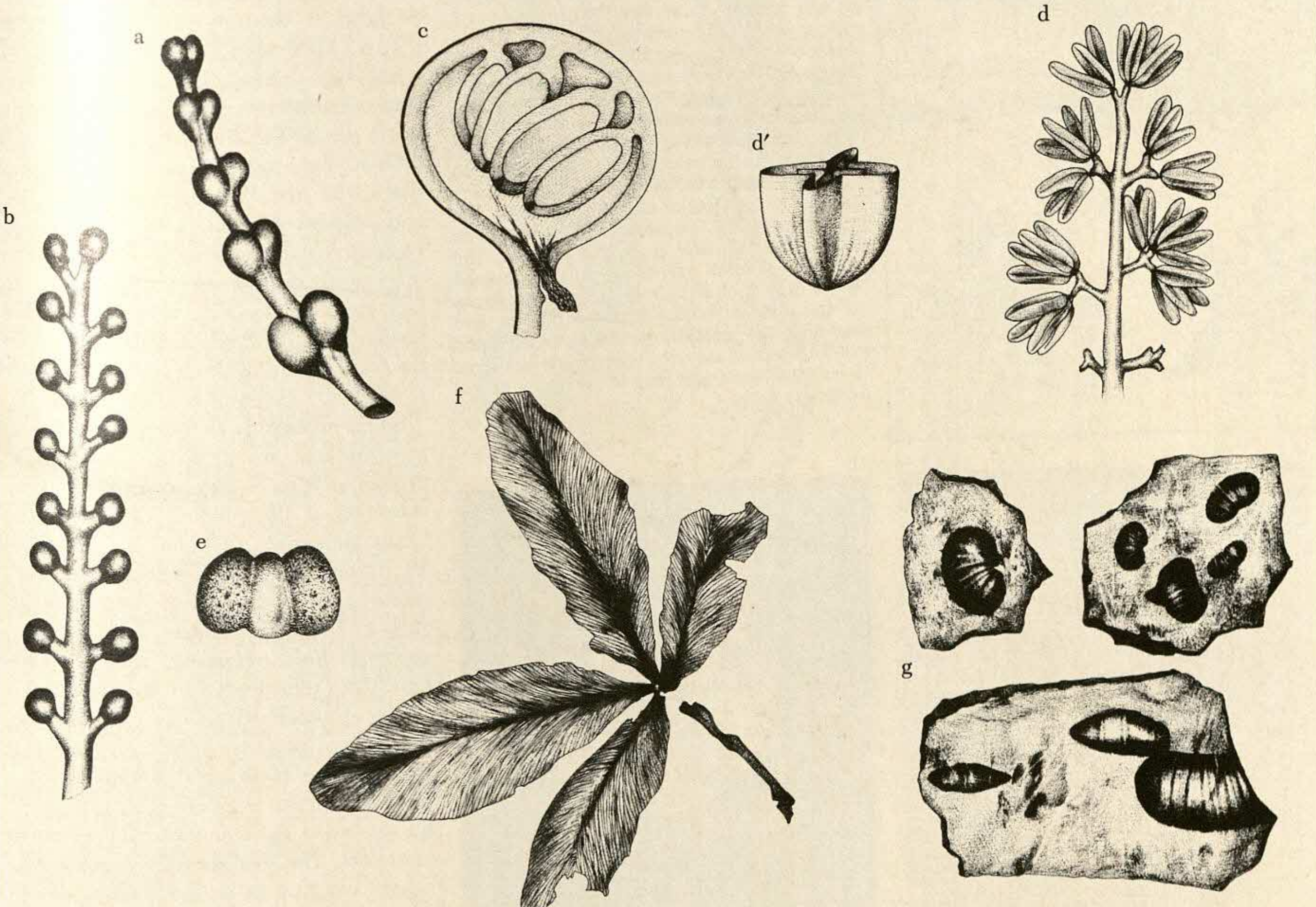
DRY AND DAMP CLIMATES

On the basis of faunal distribution, scientists have concluded that two main types of climatic zones existed during the Jurassic period—one tropical and the other temperate. The warm zones were easily distinguishable by the presence of corals, which require an environmental temperature of about 20° C (68° F), and reptiles, which have difficulty adapting to temperate and cold climates.

On the other hand, the distribution of flora seems to have been less rigorous. Nevertheless, scientists have been able to distinguish a plant association characteristic of damp regions, in which the Filicales (ferns), Cycadales (cycads), and Bennettitales (cycadeoids) appear, as well as a flora consisting mainly of conifers, characteristic of the dry regions.

THE FIRST ANGIOSPERMS — The Jurassic period was distinguished by the appearance of the angiosperms, plants that bear seeds enclosed in fruits. The first known fruit-bearing plants belonged to the order Caytoniales. These drawings depict several of the organs and important parts of members of this plant group: a megasporophyll **a** of *Griffithia nathorsti;* a megasporophyll **b** of *Gristhorpia nathorsti;* a fruit-bearing tuber **c** of *Caytonia sewardi;* a microsporophyll **d, d′** of *Caytonia sewardi;* a pollen grain **e** of *Caytonia sewardi;* and a branch and leaves **f** of *Sagenopteris phillipsi.*

The spherules **g** were perhaps the first fruits to appear on the Earth. They may be considered as fruit of *Caytonia* from the region of Sweden. However, they could equally well be sporocarps belonging to the *Marsilliaceae.*



THE CHORDATES | the vertebrates and their primitive relatives

Chordates are animals characterized by an elongated, flexible supporting rod or notochord extending the length of the body, by a hollow nerve tube extending along the back above the notochord, and by bilateral symmetry.

The notochord, which probably derived from a thickening of the wall of a primitive intestine, persists today only in the least evolved chordates and in the embryos of all vertebrates. As a vertebrate develops, the notochord is replaced by bony structures (the vertebras of the vertebral column or spine) that provide support for the body. A vertebrate has a central nervous system partially enclosed in the vertebral column or backbone and connected with a brain located in the head. Pairs of nerves emanate from the spinal column at certain intervals and provide connections with the exterior skin, the muscles, and various internal organs.

The body of a vertebrate typically consists of three distinct parts—head, trunk, and limbs—and usually extends toward the rear into a powerfully muscled tail. Two pairs of limbs are common, but in some representatives these are partially or completely lacking. In forms possessing limbs, special modifications for the type of locomotion characteristic of the animals are also present. The internal skeleton, formed of bony and/or cartilaginous tissue, is the foremost characteristic of the vertebrates; the skeleton is particularly important to paleontologists, because it is the only part of a vertebrate that is commonly fossilized.

The first animals that can be classified with certainty as vertebrates appeared on Earth during the Silurian period, over 400 million years ago. These primitive chordates, the first fish, had fairly complex and well-developed structures; therefore, paleontologists believe that these fish originated during an earlier time. In fact, rocks of the Ordovician period have yielded fragmentary remains of fish, but the fossil record of these earlier chordates is markedly incomplete.

Some organisms formerly classified as invertebrates are presently classified as protochordates. They constitute three subphyla of the phylum Chordata: the Cephalochordata (typified by the lancelet, *Amphioxus*); the Hemichordata (represented by wormlike marine animals, such as the pterobranchs, and the enteropneust *Balanoglossus*); and the Urochordata (represented by the tunicates).

The protochordates are not merely transitional organisms, bridging the gap between the invertebrates and the vertebrates; rather, they are the products of an evolution from a group of common ancestors. The evolutionary process, evidently working in different ways, led in time to the differentiation of the vertebrates and the three groups of proto-

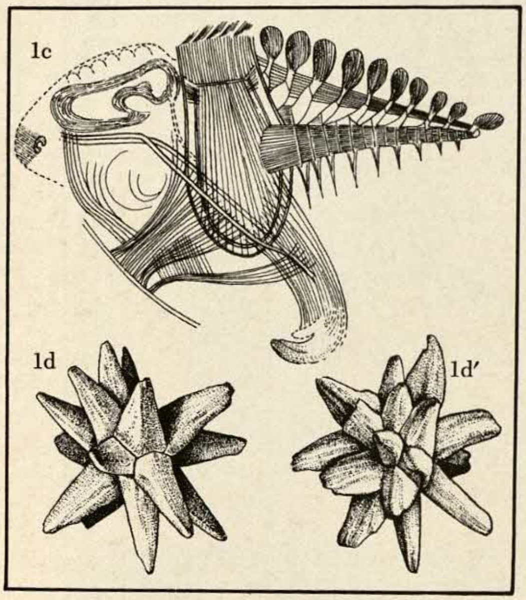
---

THE UROCHORDATES—A large portion of modern-day marine fauna consists of urochordates or tunicates, of which *Clavelina* (Illustration 1a) and *Halocyntia* (Illustration 1b) are examples. The tunicates are animals of extremely varied habitats. Some live anchored to the floor of the sea; others are planktonic, and still others are nektonic. They have been classified as members of the phylum Chordata because in the embryonic stage they possess both a nerve tube and a dorsal cord, which is limited to forming the support axis of the caudal region.

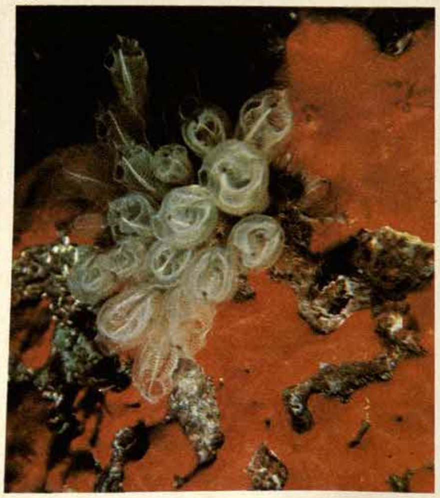
In the ascidians or sea squirts—perhaps the most representative members of the group—the dorsal cord and tail disappear during the metamorphosis from the tadpole larval stage into the first stage capable of feeding. A substance called tunicin is secreted by the skin to form a tunic (hence the name *tunicate*) with a calcareous spine or with various incrustations that can fossilize. The tunic has two functions: it provides a certain structural rigidity, and it serves to anchor the organism to a rock or other solid surface.

Numerous fossil organisms have been attributed to two orders of this subphylum, the Ascidiacea and the Thaliacea. Unfortunately, the state of preservation of these fossils has never permitted positive determinations.

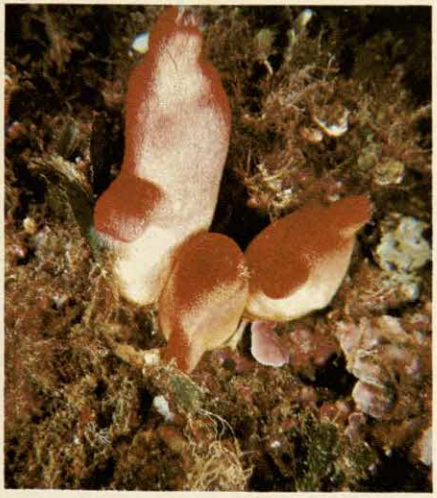
Ainiktozoon loganense (Illustration 1c) was a strange organism discovered in Silurian formations in Scotland. Classified among the urochordates, this animal had a tail similar to that of the tadpoles of living tunicates. The existence of fossil ascidians has been proved by the discovery of their spicules (Illustrations 1d and 1d′) in Tertiary strata in France and Australia. The spicules depicted are attributed to *Micrascidites vulgaris*, which does not seem to be identifiable with any of the types still in existence today.



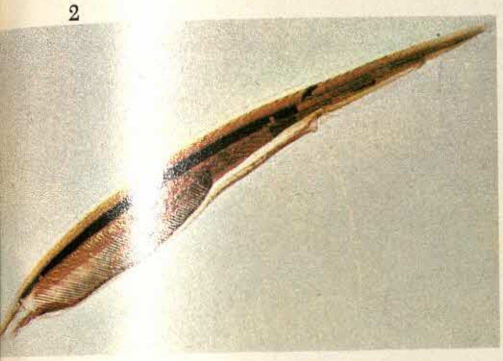
1a



1b



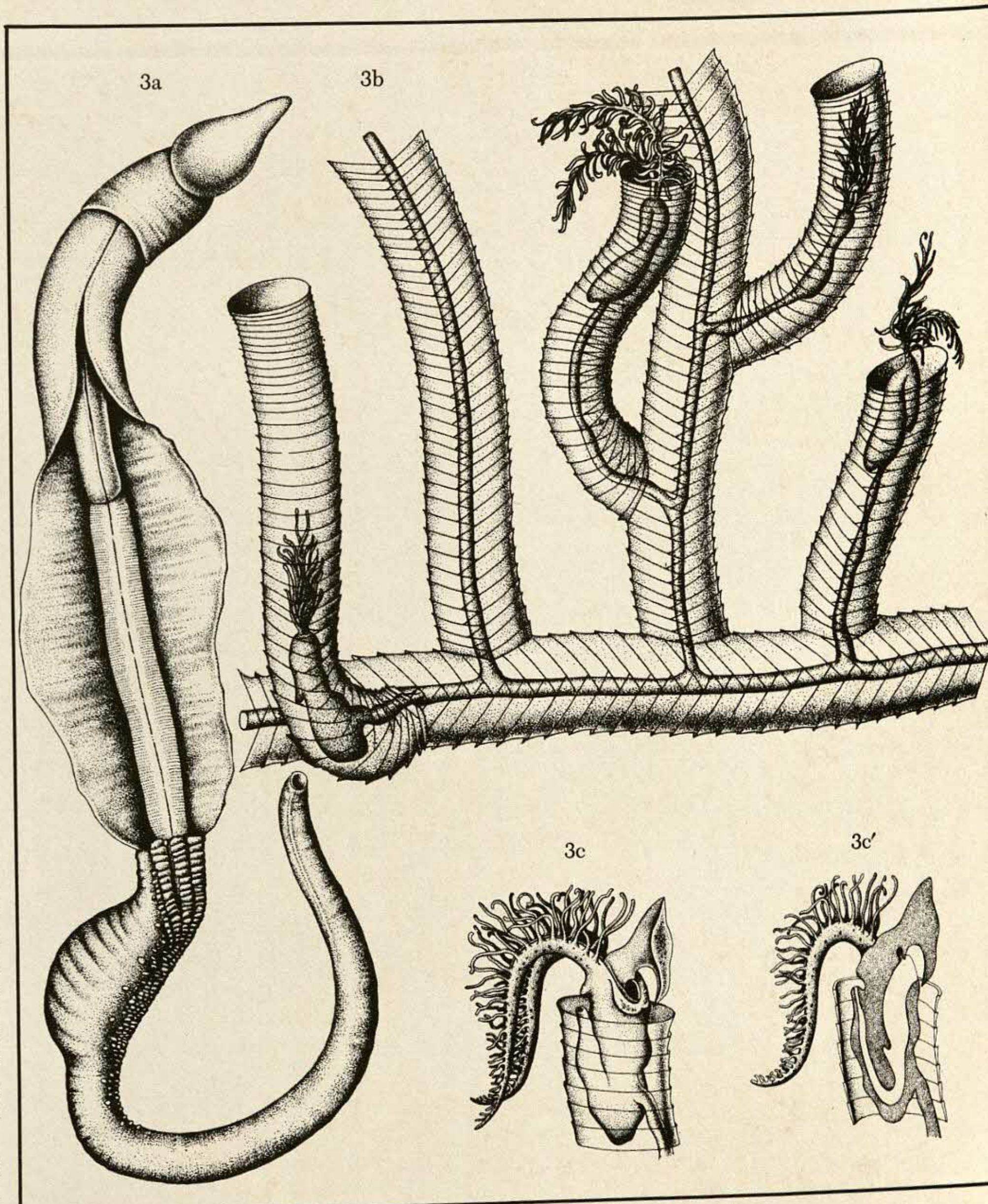
2



THE CEPHALOCHORDATES—The subphylum Cephalochordata is represented by one genus only, *Branchiostoma*, more commonly known as *Amphioxus*, which is considered the final transitional stage between the ascidians and the earliest fish. In *Amphioxus*, the notochord extends through the whole body and remains throughout the life of the organism. This form of body organization can be considered the starting point on the evolutionary scale that leads to the vertebrates. Some scientists even consider *Amphioxus* as a primitive vertebrate that underwent a process of regression. Others hold that this animal belongs to a branch other than the vertebrates—and this is perhaps the more likely hypothesis. No fossil traces of *Amphioxus* have been discovered.

chordates. Scientists, in looking for a common ancestor of all the chordates, seek a type of organism with characteristics very similar to those of the protochordates, inasmuch as these organisms followed a much shorter evolutionary path than did the vertebrates. Thus far, scientists have not definitely identified this common ancestor. In all probability, it was an organism that exhibited the first signs of formation of a dorsal axis.

The protochordates, although fewer in numbers than the vertebrates, experienced periods of great expansion in the past. The graptolites, for example, which some biologists recently have grouped among the hemichordates, experienced such an expansion during the Ordovician and Silurian periods. Most became extinct, probably because they were incapable of broad adaptation. True vertebrates, on the other hand, are characterized by great adaptability.

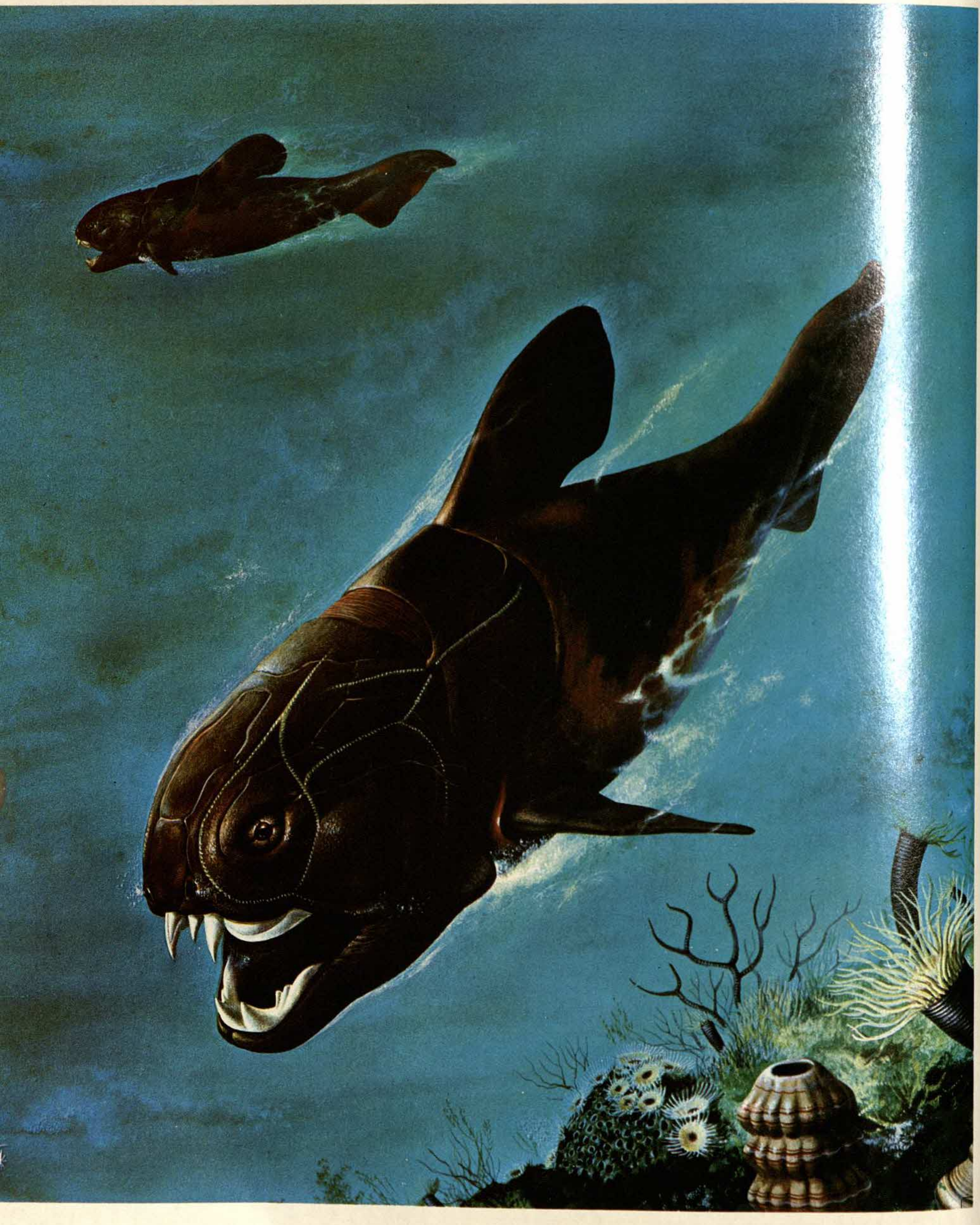


THE HEMICHORDATES—The wormlike burrowing marine animals known as hemichordates possess the barest hint of a dorsal cord. They are considered similar to both the echinoderms and the chordates. The subphylum Hemichordata includes the Pterobranchia and the Enteropneusta. The latter, as yet undiscovered in the fossil state, live buried in galleries excavated in the sea floor. The genus *Balanoglossus* (Illustration 3a) is common to the coastal waters of the Mediterranean and in many other coastal regions of the world.

Members of *Rhabdopleura*, an exclusively fossil genus of marine polyzoans, lived in colonies formed by gemmation or budding (Illustration 3b). The single individuals (shown in toto in Illustration 3c and in cross section in Illustration 3c′) were joined together by an elongated structure, the stolon. Both the stolon and the organisms were enclosed. The graptolites seem to have been very similar to *Rhabdopleura*.

PRIMITIVE FISH | the most ancient vertebrates

1



←**A DEVONIAN ARTHRODIRE**—*Dinichthys*, a Devonian fish that attained a length of about 9 m (about 30 ft), was characterized by strong teeth and thick skin plates.

Of all the vertebrate animals, fish are by far the oldest. For many millions of years they populated the waters of the Earth before venturing onto land to begin the slow evolutionary process that gave rise to land mammals and ultimately to man.

Found wherever there is permanent water, fish are cold-blooded aquatic animals having skins with many mucous glands, eyes without lids, and hearts formed of one folded tube having several chambers.

At least 30,000 species of bony fish are known to exist today—more than are included in any other class of vertebrates. Their habitats are as varied as the bodies of water in which they live—from small brooks and muddy bays to dark oceanic abysses.

Besides having importance to man as a source of food and recreation, fish also provide many valuable products, including oils, fine leather, fertilizer, glue, and isinglas.

Fish are generally divided into four classes: Agnatha, Placodermi, Chondrichthyes, and Osteichthyes.

Agnatha are primitive, jawless fish that survive today only in the Cyclostomi—the lowest class of craniate vertebrates. Agnatha, typified by lampreys and hagfishes, are abundant in fresh and salt waters of temperate regions.

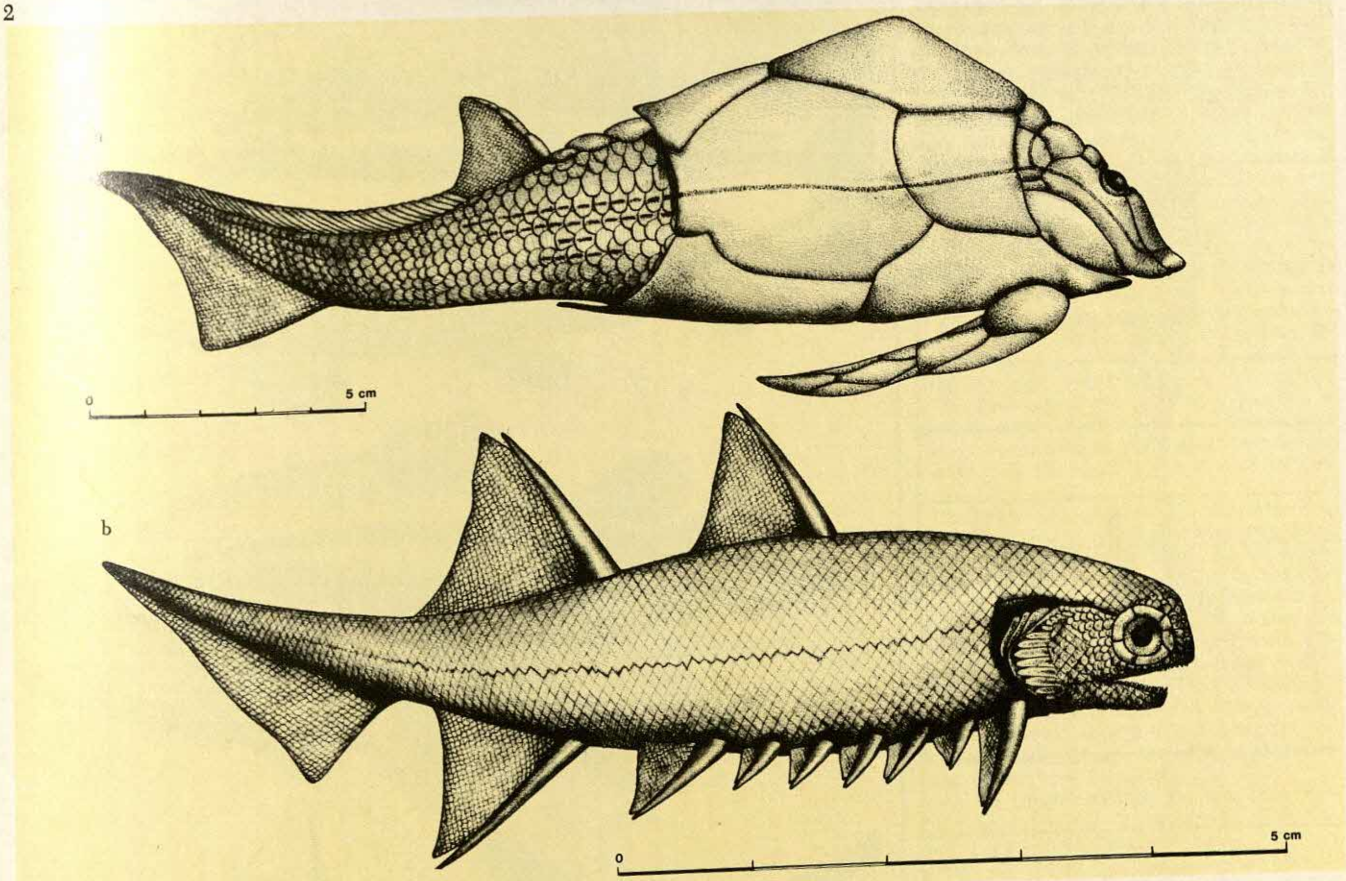
Placodermi are extinct armored fishes with jaws.

Chondrichthyes are fish, exemplified by sharks and rays, having predominantly cartilaginous skeletons.

Osteichthyes are bony fish, and include most of the popular food and game fish of today.

The first known fossil remains of the Agnatha group are the ostracoderms—aquatic vertebrates whose calcified dermal skeletons were found in the Lower Silurian strata of Colorado and in the formations of the Upper Silurian and the Devonian periods. The sediments in which they were found are typical of lake formations, indicating that the first vertebrates developed in continental fresh waters. These facts also explain the absence of ostracoderm fossils in the marine formations of the Middle Paleozoic era. In the Upper Silurian period, placoderms appeared with the ostracoderms. The complex structure of placoderms sug-

2



THE PLACODERMS—The class Placodermi lived from the Upper Silurian and Devonian until the Permian period, when they became extinct. These fish achieved their maximum numbers during the Devonian period. Generally they lived in fresh water; one group, however, lived in the sea and was the most ancient of the known marine vertebrates. The placoderms were the first vertebrates to have jaws. They are divided into four groups: Antiarcha, Acanthodii, Arthrodira, and Stegoselachii.

The head shield of the Antiarcha was made up of ossified plates, a scale-covered, movable posterior, and a pair of central fins covered by ossified plates. *Pterichthyodes* (Illustration 2a), which lived during the Devonian period, was one of the most characteristic genera.

The Acanthodii were small, freshwater fish characterized by head plates, bony scales, several pairs of ventral fins, and clearly marked gill slits. Illustration 2b is a reconstruction of a typical representative of the genus *Climatius* of the Lower Devonian period. It has several pairs of ventral fins supported by spinelets, and two strong, spined dorsal fins.

The Arthodira were freshwater fishes with a bony armored anterior body. They lived only in the Devonian. *Dinichthys* was a giant whose cephalic shield was more than 9 m (about 30 ft) long.

The Stegoselachii had a dermal skeleton composed of scales supported by plates in the anterior part of the body.

gests that vertebrates might date back further than the Ordovician and Silurian periods—perhaps even to Precambrian times.

CARTILAGINOUS AND BONY FISH

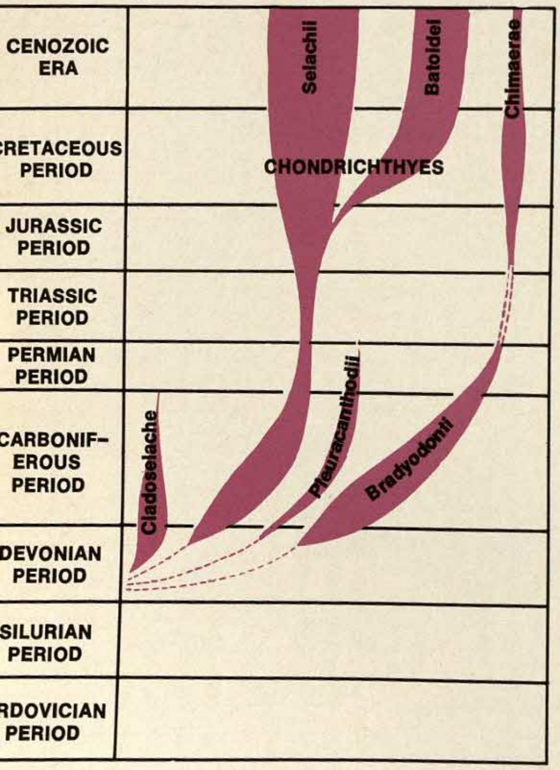
Whereas the ostracoderms and placoderms are completely extinct, the sharks and their relatives with modern jaws have many living representatives. The class Chondrichthyes, which includes both the fossil forms and the living representatives, has been divided into two subclasses: the Elasmobranchii (to which belong the sharks, skates, and rays) and the Holocephali (to which belong the modern chimaeras and a few fossil forms).

The principal characteristic of the sharklike Chondrichthyes is the presence of an internal cartilaginous skeleton that is not ossified, but that is sometimes calcified. The external body armor, highly developed in the ostracoderms and placoderms, is greatly reduced; it consists of placoid scales or denticles, toothlike structures that give the skins of present-day sharks a spiny character. Because of the lack of ossification of the endoskeleton and the great reduction in the exoskeleton, only teeth and skeleton are found in fossils—except for rare instances of exceptional preservation. Therefore, paleontological classifications are made principally on the basis of the diversity noted in these fossilized parts.

The lack of ossification of the skeleton was once considered a sign of primitiveness, but the complex structure of the jaw makes this hypothesis highly un-

EVOLUTION OF THE CHONDRICHTHYES—As this illustration indicates, the Cladoselachidae, one of the earliest representatives of the class Chondrichthyes, appeared during the Middle Devonian period. The origins of these cartilaginous fish, while still obscure, probably go back to the placoderms. During the Upper Devonian period, the Selachii, the Pleuracanthodii (Ichthyotomi), and the Bradyodonti developed; the Chimaerae evolved from the Bradyodonti early in the Jurassic period, and the Batoidei evolved from the Selachii toward the end of the same period.

3

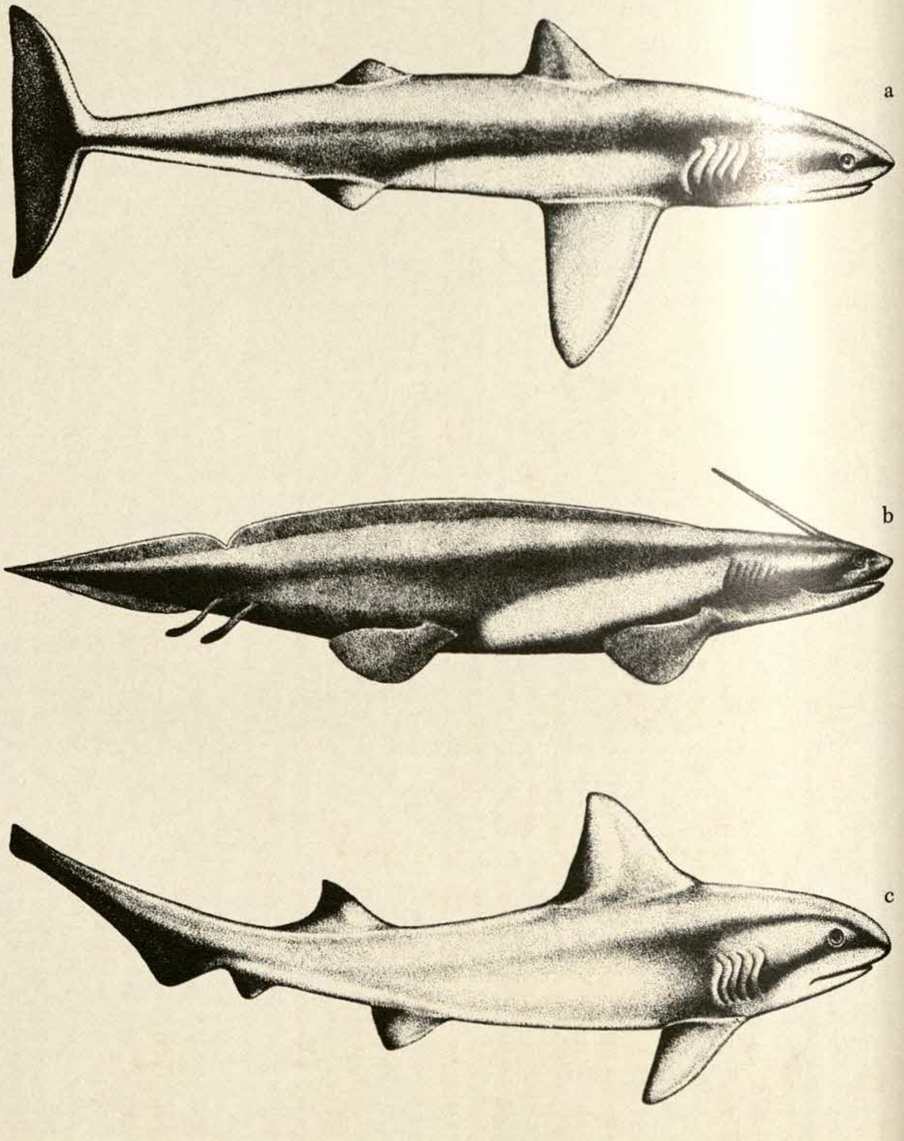


4

THE ELASMOBRANCHS—Of the primitive Elasmobranchii (or Euselachii), the members of Cladoselachidae are noteworthy. Numerous teeth, attributed to the genus *Cladodus*, have been discovered in Devonian and Carboniferous formations, thereby proving the existence of these most ancient cartilaginous fish. Devonian deposits in North America have yielded numerous whole specimens of this elasmobranch; these specimens, preserved by a special kind of fossilization, measure about 1 m (about 3 ft) in length. These primitive fossil sharks (Illustration 4a) were characterized by paired broad-based fins that made them incapable of executing the movements of their present-day successors. The Pleuracanthodii of Carboniferous and Permian times have been put in this class; the genus *Pleuracanthus* (Illustration 4b), measuring some 70 cm (about 28 in.) in length, was characterized by a long dorsal spine.

The true Selachii, which developed along with the Hybodontidae during the Upper Devonian, can almost be considered transitional between *Cladoselache* of the Middle Devonian and the modern-type Selachii. Of this group also, only the teeth have been found as fossils, except for the genus *Hybodus*, whose skeleton has been discovered; its reconstruction is shown in Illustration 4c. Modern-type Selachii, similar to present-day representatives, developed during the Cretaceous. Their teeth, which had extremely different shapes in the different species, are commonly found in marine deposits; sometimes the teeth are large enough to suggest the existence of monstrous specimens. A common genus was *Lamna*, whose teeth have been found widely distributed throughout Cretaceous and Tertiary formations in Italy.

The rays (Batoidei), which arose from the aforementioned groups, are forms adapted to benthic living; in fact, they have flattened bodies and their eyes and paired fins have migrated to form a kind of garland around the body. They are noted above all for their generally flattened subrectangular teeth.



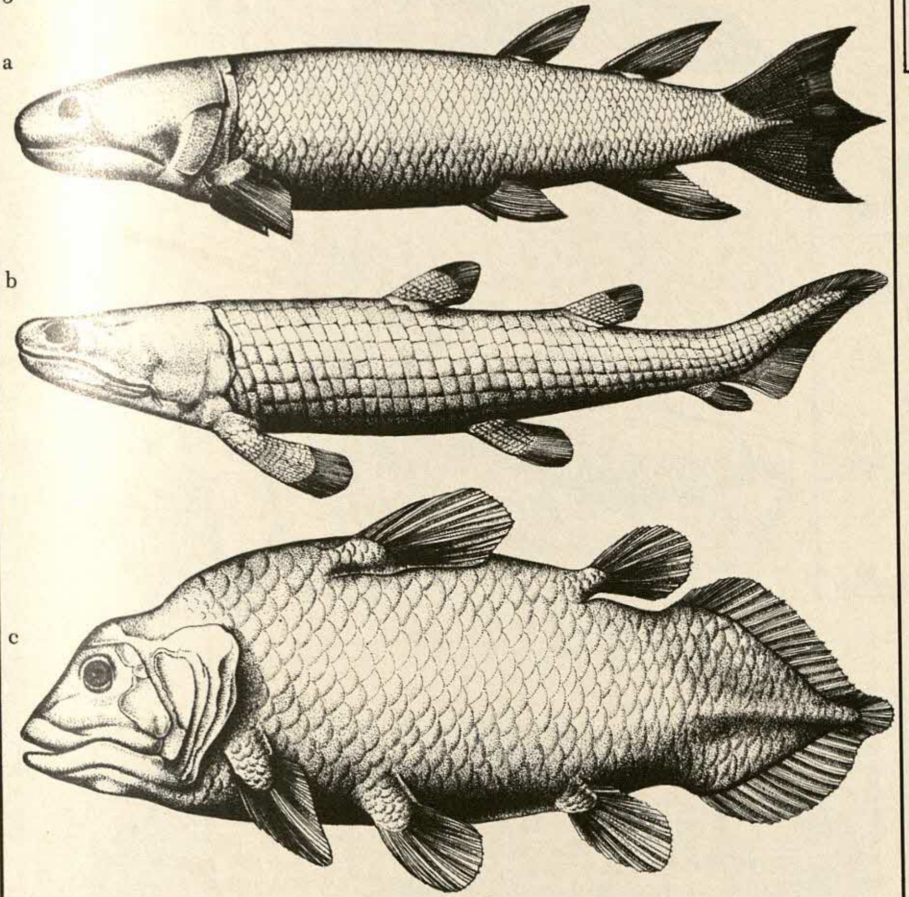
likely. Presently the Chondrichthyes are considered to be of the same age as the bony fish or Osteichthyes. The first representatives of both classes appeared together in the Middle Devonian. This fact excludes the possibility that one group was derived from the other.

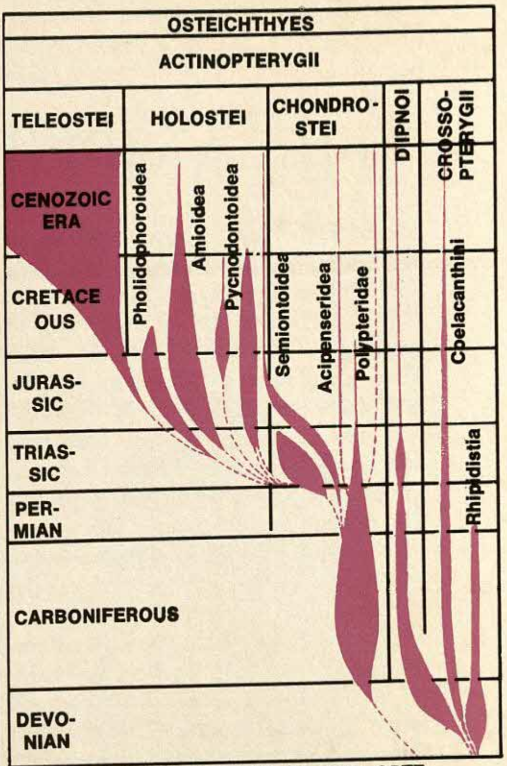
The Chondrichthyes are thought to have descended from the ancient Placodermi, although transitional forms between the two classes are unknown. Moreover, the Elasmobranchii and the Holocephali are believed to have evolved simultaneously.

THE CROSSOPTERYGII—In the study of the evolution of terrestrial vertebrates, paleontologists attach great importance to the primitive crossopterygians, from which the first amphibians seem to have been derived. The structurally complex teeth of these primitive fish, when observed in cross section, reveal folds in the dentine and enamel similar to those found in the teeth of the primitive amphibians known as the labyrinthodonts. Furthermore, the brain case of the crossopterygians is divided into front and back halves with a primitive articulation; the same configuration is found in the embryos of some vertebrates and persists in many amphibians and reptiles. The skull and jaw structures of early fishlike amphibians also resemble these structures in the crossopterygians.

The first crossopterygians appeared during the Lower Devonian, and representatives of the group lived during the Mesozoic era with freshwater forms of the order Coelacanthani, which includes the important genera of *Osteolepsis* (Illustration 5a) and *Eusthenopteron* (Illustration 5b) of the Devonian and *Undina* (Illustration 5c) of the Triassic and Jurassic. The only living coelacanth is *Latimeria* (Illustration 5d), which was first discovered in 1938 in deep waters off the coast of South Africa. Until this discovery, the crossopterygians had been considered long extinct. The discovery of *Latimeria* indicates that, sometime between the Mesozoic and the present, the crossopterygians changed their habitat from continental fresh waters to deep sea waters.

5





ORIGINS AND EVOLUTION OF THE OSTEICHTHYES—In contrast with the agnathans and placoderms, which became extinct during the course of geologic time, and the selachians or cartilaginous fish, whose importance has greatly diminished in the present day, the bony fish (class Osteichthyes) are flourishing today. The class is represented by the animals best adapted to aquatic environs. These animals, of course, possess ossified internal skeletons which, preserved in the fossil state, have led to their classification as bony fish. The exoskeleton consists of regularly placed scales that are mainly of two types: ganoid scales in the ray-finned fish (Actinopterygii) and cosmoid scales in the Dipnoi and Crossopterygii.

The evolutionary history of the bony fish began in continental fresh waters, as did that of the Placodermi, but most bony fish live in oceanic waters today. The few members of Osteichthyes living in continental waters now are the only fish found in this kind of environment.

The class Osteichthyes (Pisces), which includes numerous representatives, has been subdivided into two subclasses, the Choanichthyes and the Actinopterygii. The former consists of fleshy-finned fish characterized by internal nostrils (choanae) and includes the Crossopterygii and the Dipnoi. The latter consists of ray-finned fish that, lacking internal nostrils, engage in pharyngeal respiration by means of respiratory sacs that in most cases have been transformed into swimbladders; the subclass Actinopterygii includes the Holostei, Chondrostei, and Teleostei.

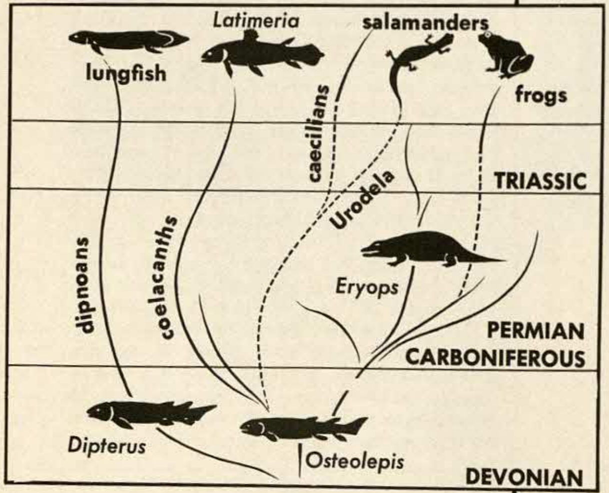
As the chart indicates, the first bony fish, the Dipnoi and the Crossopterygii, appeared during the Middle Devonian. These fish were widely distributed throughout the balance of the Paleozoic era and into the Triassic period of the Mesozoic era, but today they are relatively few in numbers. The Chondrostei appeared in the Upper Devonian and became widespread during the latter part of the Paleozoic, but they too are rarely found today. The Holostei developed from the Chondrostei during the Triassic, and the Teleostei developed from the Holostei in the Jurassic.

THE AMPHIBIANS | at home on land and in water

Not until the late Devonian period, in the middle of the Paleozoic era more than 350 million years ago, did vertebrates first leave the sea and begin to spend part of their lives on dry land. These vertebrates are known as amphibians (from the Greek words for "double" and "life") because they are both land and water animals, transitional between the fish (Pisces) and reptiles (Reptilia). The direct ancestors of amphibians were lobe-finned fish, the Crossopterygii, which had similar dental and cranial structures.

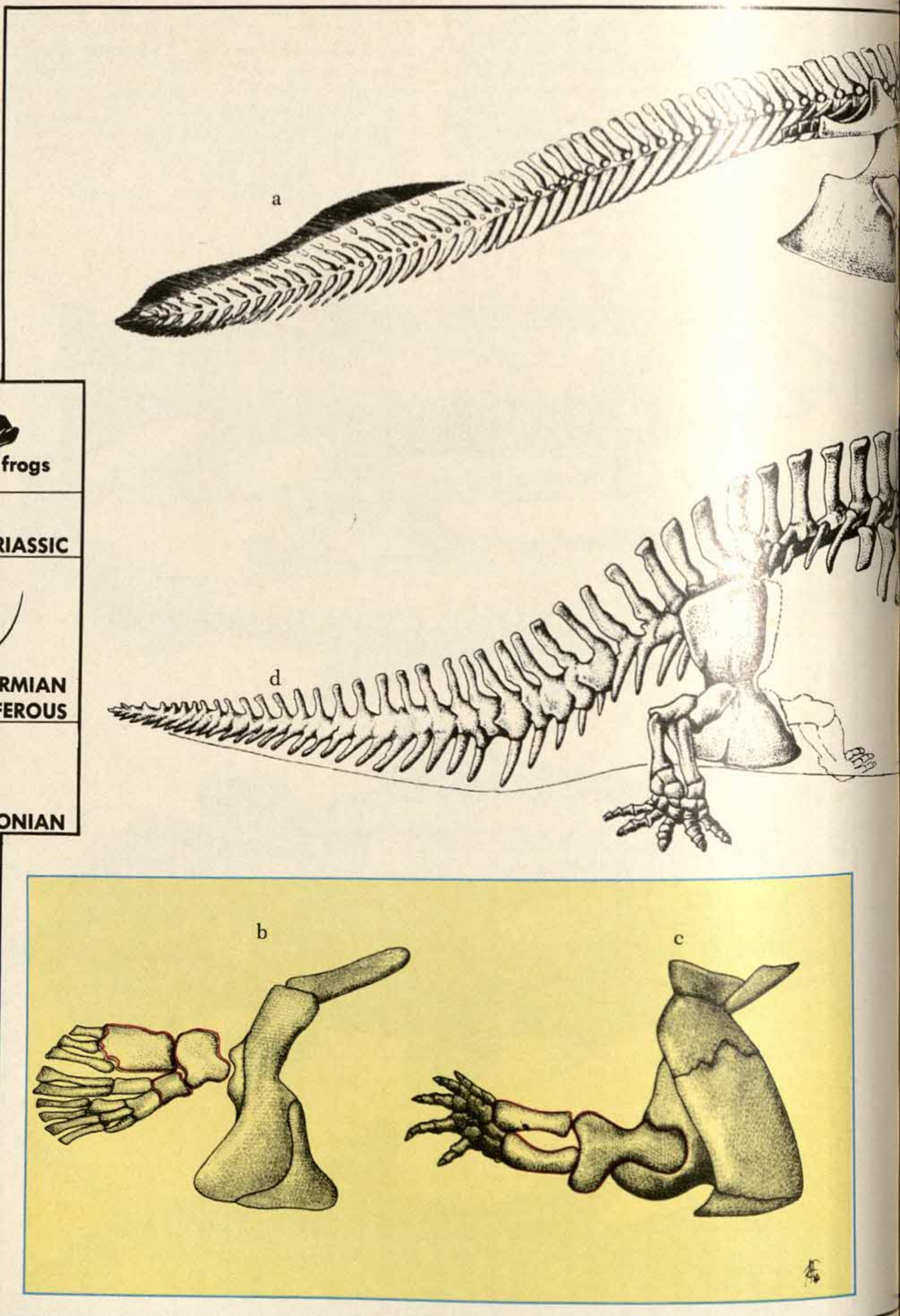
In order to live on land, the first amphibians had to adapt to their new habitat by breathing in a new way—through lungs, directly from air, rather than through gills that utilized the air dissolved in water. (The crossopterygians were also developing lungs, found today in their direct descendant, the lungfish.) Their fins became limbs that allowed them to move on land, where the buoyant force of water was no longer available to support the weight of their bodies; and they developed strong axial skeletons. Other morphological adaptations were the development of optical

1

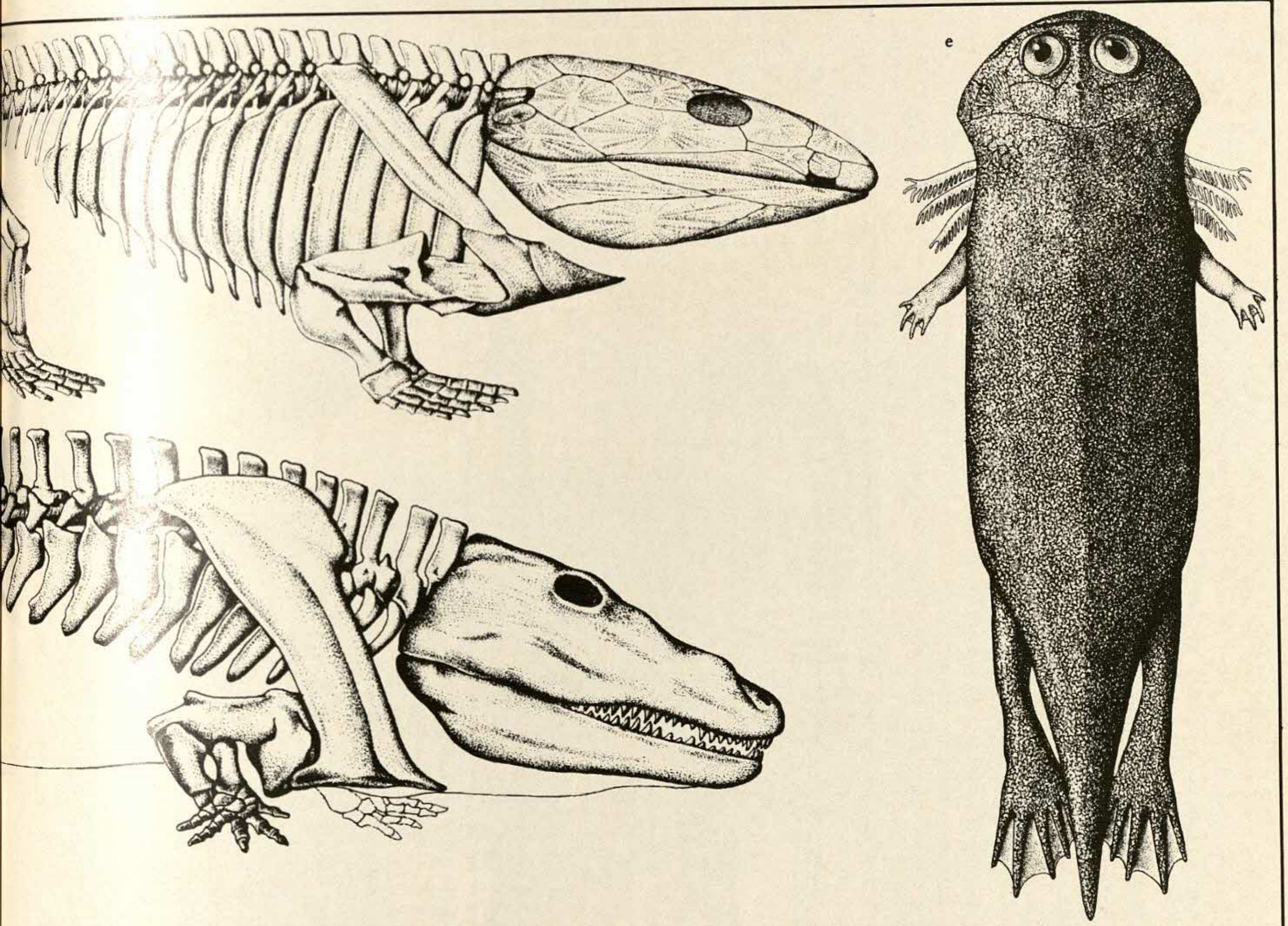


THE EVOLUTION OF AMPHIBIANS—The first amphibians evolved from lobe-finned fishes, the Crossopterygii, in the late Devonian period. These were Labyrinthodontia, found over a wide area. They were followed, in the Carboniferous and Permian periods, by other amphibians of the subclass Lepospondyli. At the end of the Palaeozoic era the amphibians, which had previously been the only land-dwelling vertebrates, began to decline rapidly as a result of the spread of the reptiles, which were more competent in the struggle to survive. During the Triassic, the first period of the Mesozoic era, there were fewer amphibians, but among the Salientia appeared the first anurans, ancestors of the frogs. During the next period, the Jurassic, the previous large amphibians disappeared; among the Apsidospondyli only the Anura remained, and the only survivors among the Lepospondyli were the Urodela and the Apoda, the ancestors of the present salamanders and caecilians.

2



apertures and eardrums. Despite these changes, the amphibians were still linked to the water, for only in an aqueous environment could they reproduce by means of the soft, unprotected eggs inherited from their fish ancestors. Consequently, the amphibians spent the first part of their lives—their larval stage—in the water. Only a shelled egg, with its amniotic fluid providing a protected environment for the young, could make the vertebrate independent of the water, and this was not achieved until the reptiles evolved in the later Permian period, about 100 million years later. The limb-



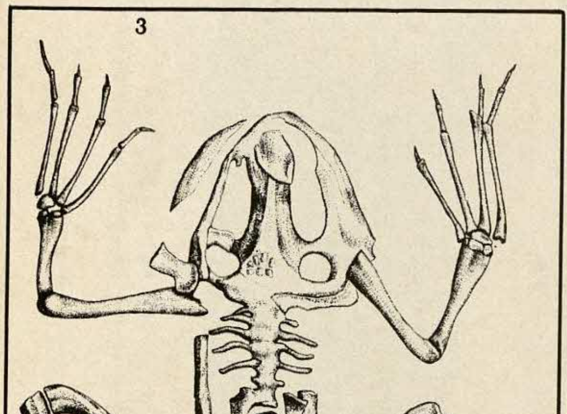
THE LABYRINTHODONTS — The superorder Labyrinthodonta, also known as Stegocephalia, includes fairly primitive forms of the subclass Apsidospondyli, the earliest of the amphibians. Such forms are characterized by highly folded teeth, derived from the crossopterygian fishes, and by a cranium covered by bony plates with two nasal openings, two eye sockets, and one pineal orifice. The low, wide cranium, which accounts for the name Stegocephalia, is one of the characteristics peculiar to this group, which includes very large forms that flourished from the late Devonian to the Triassic. The most ancient and most primitive seem to have lived almost entirely in the water, but during the Carboniferous, genera evolved that adapted to a life on dry land. In the Triassic, the labyrinthodonts returned to the water, and it is probable that the first reptiles evolved from this group of amphibians during the Permian.

There seems no doubt that the first and most primitive of the amphibians was *Ichthyostega* (Illustration 2a), about three feet long, of which numerous fossils have been found in lacustrine deposits in Greenland. Its skull resembles that of the crossopterygians in the number and arrangement of the bones; its limbs (Illustration 2c) are not strong and seem to have evolved from the fins (Illustration 2b) of this group of fishes; the tail is long, with a median fin supported by bony projections that suggest an exclusively aquatic life. Most of the conspicuous fossils belong to a group that is now extinct. These include *Eryops* (Illustration 2d), six feet long, that appears to have been well adapted to land in the Permian; *Cacops*, even more adapted for walking, and much stronger; *Eogyrinus*, of the Carboniferous period; and *Gerrothorax* (Illustration 2e), of the Triassic period, with a wide and very flattened head, which appears to represent the maximum degree of specialization among the labyrinthodonts and is considered the last of this superorder.

less larvae of the amphibians, born from the soft eggs laid in the water, were provided with gills like those of their fish ancestors and did not leave the water until they became adult.

The amphibian skeleton differed from that of the crossopterygian fish in that it had a sturdy spinal column composed of differentiated vertebrae, with cervical, lumbar, sacral, and caudal elements. The greater strength these provided was required because the development of front and rear limbs raised the body off the ground. The early amphibians are classified according to the structure and characteristics of their vertebrae; on the basis of both fossil and existing amphibian skeletons, two subclasses have been distinguished: the Apsidospondyli and the Lepospondyli. The former include the superorder Labyrinthodontia, all of whose forms are extinct, and the superorder Salientia, ancestors of the frogs. The Lepospondyli, which appeared later, included numerous extinct forms and also the Urodela—ancestors of the newts and salamanders—and Apoda (or caecilians), ancestors of existing wormlike amphibians native to the tropics. Caecilian relationship to a lepospondylous form is based on skull anatomy. No fossil record exists for caecilians; comparisons must be made between living forms and their fossil relatives.

3

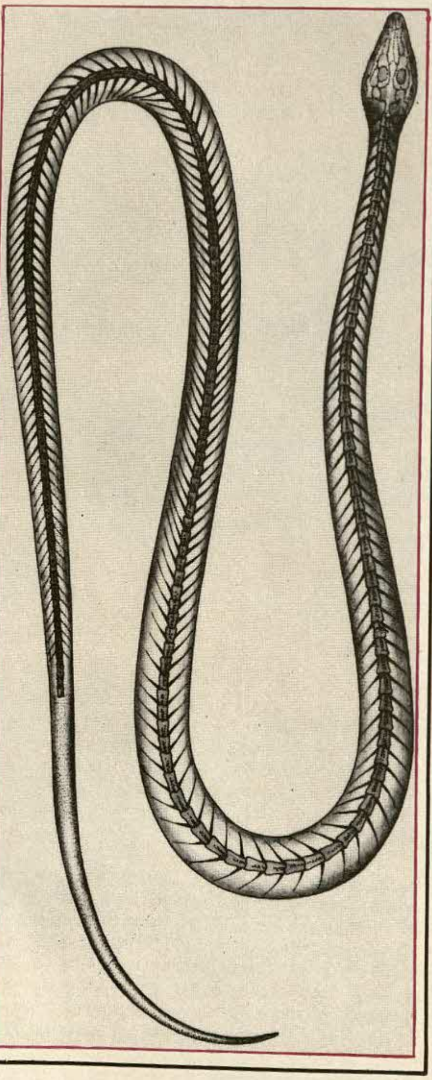


THE SALIENTIA—The labyrinthodonts disappeared in the Triassic, but another superorder of Apsidospondyli survived—the Salientia, ancestors of the Anura or frogs. (The reptiles, probably derived from labyrinthodonts, not only survived but eventually prevailed over all the amphibians.)

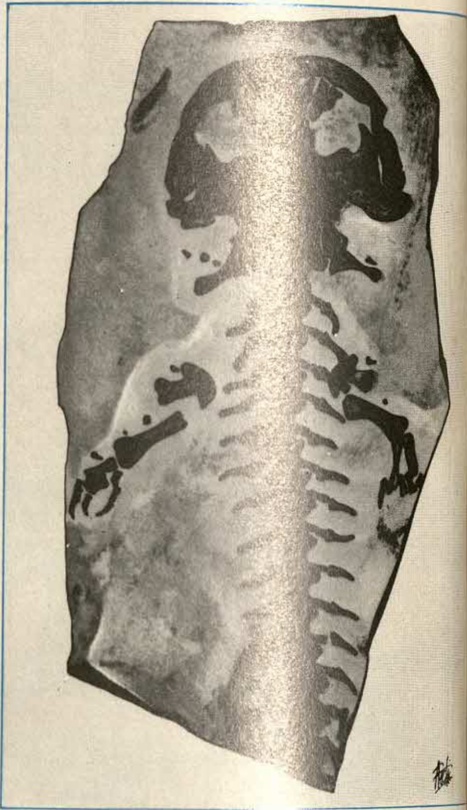
The Salientia exemplify almost spectacular specialization, developing in the course of their evolution the ability to jump. One result was a considerable reduction in size. The most primitive was the *Protobatrachus* of the early Triassic period, with a squat body, hind legs not yet adapted to jumping, and a rudimentary tail; its skull, however, was almost identical to that of the modern frog. Anura of the Jurassic and later periods have been found with decidedly modern structure, greatly reduced size, a large and flat head, shortened and tailless hindquarters, elongated hind legs, and quite short front limbs. They did not become abundant until the Cenozoic era, and their similarity to existing forms is apparent from the bones (illustrated) of *Palaeobatrachus*, which flourished in the Oligocene or Miocene.

THE LEPOSPONDYLS—The Lepospondyli are a subclass of amphibians that flourished during the Carboniferous and Permian periods, and were the ancestors of the present caecilians (Apoda) and Urodela. When the Lepospondyli first appeared in the early Carboniferous, their forms were very small and adapted to living in swamps. They included *Diplocaulus* of the Permian, well adapted to living in the water and characterized by a curious triangular skull with wide lateral projections of the cranial bones and by a flat body with tiny, weak feet. They also included *Dolichosoma*, shown in this illustration, representative of genera of the late Carboniferous, with snakelike bodies. No fossils classified as belonging to the Apoda have been identified; their descendants are the caecilians that now inhabit tropical climates and are characterized by snakelike bodies without limbs. The lepospondyls are also the remote ancestors of the existing Urodela—salamanders and newts—derived from forms that appeared about 100 million years ago in the late Cretaceous period.

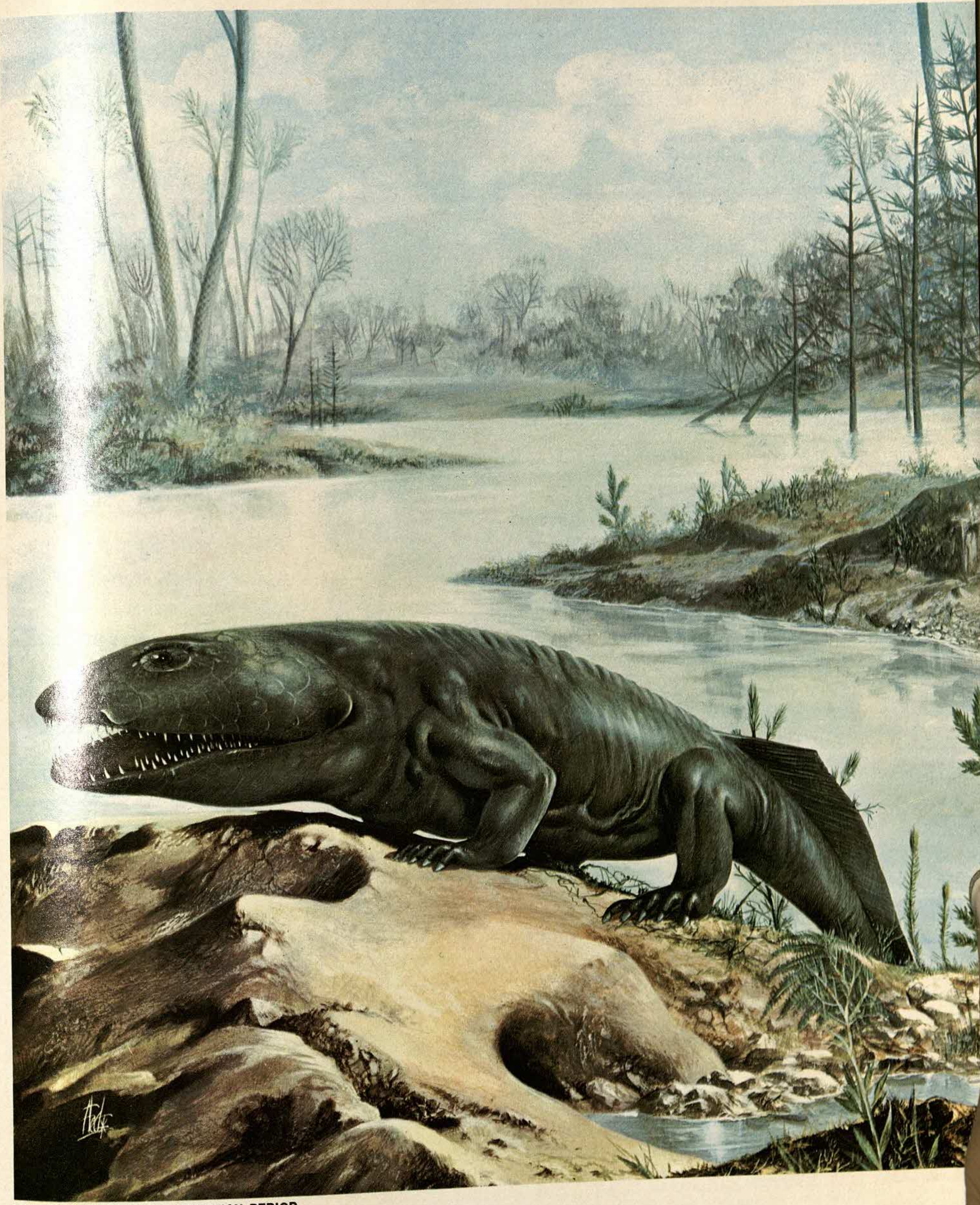
4



5



A STRANGE FOSSIL—One of the Urodela, an ancestor of the salamanders, was *Andrias*, found in European terrain of the Miocene epoch. This fossil, of the species *Andrias scheuchzeri*, about three feet long, was described in 1726 as *Homo Diluvii Testis*—the remains of a man drowned in the biblical Deluge—according to the primitive notions of paleontology then prevalent; it was called "one of the rarest relics we have of this cursed race that was buried by the waters."



A SWAMP OF THE LATE DEVONIAN PERIOD —Shown is a specimen of *Ichthyostega,* a transitional vertebrate between the fishes and the amphibians, and usually considered the first capable of moving on dry land. It lived about 350 million years ago.

ABBREVIATIONS

A	ampere
Å	Ångstrom unit
abs	absolute
a-c	alternating current (as an adjective)
amu	atomic mass unit
atm	atmosphere
at. wt	atomic weight
AU	astronomical unit
avdp	avoirdupois
Bev	one billion electron volts
bhp	brake horsepower
bhp-hr	brake horsepower-hour
bp	boiling point
Btu	British thermal unit
C	temperature Celsius; temperature Centigrade
c	candle
cal	calorie
cfm	cubic feet per minute
cfs	cubic feet per second
cgs	centimeter-gram-second (system)
cl	centiliter
cm	centimeter
cm^2	square centimeter
cm^3	cubic centimeter
coef	coefficient
colog	cologarithm
cos	cosine
cot	cotangent
cp	candlepower
csc	cosecant
cu	cubic
cu ft	cubic foot
db	decibel
d-c	direct current (as an adjective)
doz	dozen
E	electromotive force
e	the base of the system of natural logarithms
ev	electron volt
F	temperature Fahrenheit
fp	freezing point
fpm	feet per minute
fps	feet per second
ft	foot; feet
ft^2	square foot
ft^3	cubic foot

ft-c	footcandle
ft-lb	foot-pound
G	universal gravitational constant
g	gram
gal	gallon
g-cal	gram-calorie
gpm	gallons per minute
gps	gallons per second
hr	hour
hν	photon energy
hp	horsepower
Hz	hertz (cycles per second)
I	electric current
ID	inside diameter
in.	inch
in.^{2}	square inch
in.^{3}	cubic inch
in.-lb	inch-pound
ips	inches per second
j	joule
K	temperature Kelvin (absolute)
kcal	kilocalorie
kg	kilogram
kg-cal	kilogram-calorie
kg-m	kilogram-meter
kg/m^3	kilograms per cubic meter
kgps	kilograms per second
km	kilometer
kv	kilovolt
kw	kilowatt
kwhr	kilowatt-hour
l	liter; lumen
lat	latitude
lb	pound
lb-ft	pound-foot
lb/ft^2	pounds per square foot
lb/ft^3	pounds per cubic foot
lb-in.	pound-inch
l-hr	lumen-hour
lin ft	linear foot
log	logarithm (common)
log$_e$	logarithm (natural)
long.	longitude
m	meter; minute (time, in astronomical circles)

m^2	square meter
m^3	cubic meter
ma	milliampere
Mev	one million electron volts
mg	milligram
mh	millihenry
mi	mile
mi^2	square mile
min	minute
m-kg	meter-kilogram
ml	milliliter
mm	millimeter
mm^2	square millimeter
mm^3	cubic millimeter
mμ	millimicron
mph	miles per hour
mphps	miles per hour per second
mv	millivolt
N	Avogadro's constant
$n!$	factorial n
OD	outside diameter
oz	ounce
pH	rating on acid-alkaline scale
ppm	parts per million
psi	pounds per square inch
psia	pounds per square inch absolute
R	temperature Reaumur; resistance
RA	right ascension
rpm	revolutions per minute
rps	revolutions per second
sec	secant; second
sin	sine
sp gr	specific gravity
sq	square
tan	tangent
V	volt
VA	volt-ampere
W	watt; work
yd	yard
yd^2	square yard
yd^3	cubic yard

SCIENTIFIC SYMBOLS AND ABBREVIATIONS

α	alpha particle
β; β^-	beta particle
β^+	positron
γ	gamma radiation
Δ	a small change; heat
λ	wavelength; radioactive-decay constant
ma	milliampere
μc	microcurie
μf	microfarad
μin.	microinch
μm	micron
$\mu\mu$	micromicron
$\mu\mu$f	micromicrofarad
ν	frequency; neutrino
π	3.14159; osmotic pressure

Σ	the sum of
σ	nuclear cross section (barns); area
Ω	electrical resistance (ohms)
ω	angular speed; angular velocity
$'$	minute (angular measure)
$''$	second (angular measure)
♂	male
♀	female
$>$	is greater than
$<$	is less than
$\propto$	is proportional to
∞	infinity
$\sqrt{\ }$	square root of
$^\circ$	degrees; temperature; angle measurement (example, 30°)

[ ]	molar concentration
$+$	positive electric charge; mixed with; plus
$-$	negative electric charge; single covalent bond; minus
$=$	equals; double covalent bond; produces
$\neq$	does not equal
$\equiv$	triple covalent bond
$\rightarrow$	produces; forms; chemical reaction
$\rightleftarrows$	reversible chemical reaction
$\uparrow$	gas produced by a chemical reaction
$\downarrow$	precipitate produced by a chemical reaction
*	radioactive substance (follows symbol of element; example, Cl*)

THE
ILLUSTRATED SCIENCE
DICTIONARY

Conjugation to Deferent

KEY TO PRONUNCIATION

The diacritical marks are:

ə	b*a*nan*a*, *a*but
ᵊ	preceding l, m, n as in battl*e*
ə̇	*e*lectric
ər	f*ur*ther
a	m*a*t
ā	d*ay*
ä	cot, f*a*ther
au̇	n*ow*, *ou*t
e	b*e*t
ē	b*ea*t
i	t*i*p
ī	b*i*te
j	*j*ob, gem
ŋ	si*ng*
ō	b*o*ne
ȯ	*saw*, *a*ll
ȯi	c*oi*n
th	*th*in
t̲h̲	*th*en
ü	r*u*le, f*oo*l
u̇	p*u*ll, w*oo*d
ue	German h*ü*bsch
u̅e̅	French r*ue*
yü	*u*nion
zh	vi*si*on

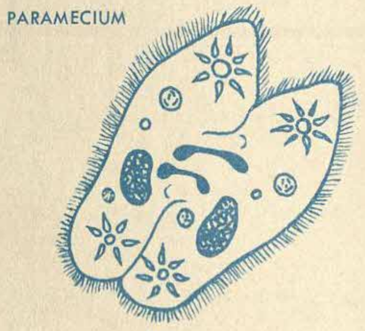
ˈ mark preceding the syllable with strongest stress.

ˌ mark preceding a syllable with secondary stress.

The system of indicating pronunciation in these volumes is used by permission from Webster's *Third New International Dictionary*, copyright 1961 by G. & C. Merriam Co., Publishers of the Merriam-Webster Dictionaries.

conjugation \ˌkän-jə-'gā-shən\ *n.*
BIOLOGY. A form of sexual reproduction in which there is an interchange of nuclear material between two similar gametes or two unicellular organisms; a process somewhat like fertilization.

The paramecium reproduces asexually by mitotic cell division and sexually by CONJUGATION.



CONJUGATION

conjunction \kən-'jəŋ(k)-shən\ *n.*
ASTRONOMY. A lining up of two or more celestial objects, such as a planet and the sun, when viewed from the earth.

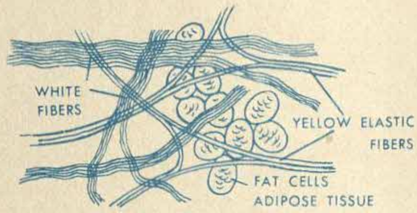
A planet in front of the sun is said to be in inferior CONJUNCTION, *while a planet behind the sun is in superior conjunction.*

conjunctiva \ˌkän-ˌjəŋk-'tī-və\ *n.*
ANATOMY. A delicate mucous membrane that lines the inner surface of the eyelids and covers the front part of the eyeball.

Tears tend to keep the CONJUNCTIVA *free from irritating particles.*

connective tissue \kə-'nek-tiv 'tish-(ˌ)ü\
ANATOMY. Any fibrous tissue that binds together and gives support to the various structures of the body.

Cartilage, a CONNECTIVE TISSUE *that holds bones together at the joints, is somewhat elastic.*



CONNECTIVE TISSUE

conodont \'kōn-ə-ˌdänt\ *n.*
EARTH SCIENCE. A tiny toothlike fossil, composed of calcium phosphate, that is found in some limestones and slates of the Paleozoic Era.

Some paleontologists believe that a CONODONT *is the tooth of a primitive fish, but others believe that it is a mouthpart of a sea worm.*

conservation \ˌkän(t)-sər-'vā-shən\ *n.*
BIOLOGY and EARTH SCIENCE. The protection, care and wise use of land, forests, water, animal life, minerals and fuels.

Erosion control is important in soil CONSERVATION.

CONSERVATION

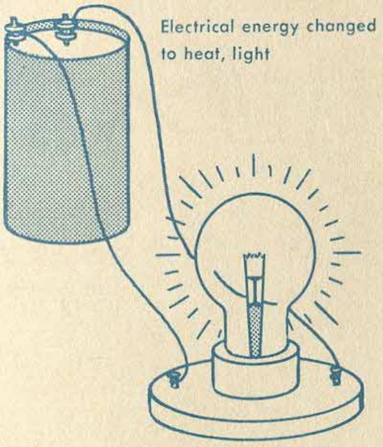
Soil erosion

Soil erosion stopped by planting trees

conservation of energy \ˌkän(t)-sər-'vā-shən əv 'en-ər-gē\
A principle stating that the total amount of energy in a closed system is constant. According to this principle, energy may be changed from one form to another but never created or de-

stroyed, except in nuclear reactions. In these, energy may be converted into small amounts of matter, or vice versa.

CONSERVATION OF ENERGY *is illustrated when electrical energy is converted into heat and light by atoms in a lamp bulb filament.*



CONSERVATION OF ENERGY

conservation of mass \ˌkän(t)-sər-ˈvā-shən əv ˈmas\
PHYSICS. A law stating that the total mass of a material system is not changed by reactions between individual parts of the system.

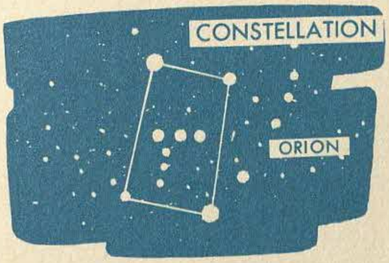
The law of CONSERVATION OF MASS *holds true in terms of ordinary physical and chemical changes, but it is inconsistent with newer theories that define matter as a form of energy.*

conservation of matter \ˌkän(t)-sər-ˈvā-shən əv ˈmat-ər\
A principle stating that the total amount of matter in a closed system is constant. According to this principle, matter can be changed from one form to another but never created or destroyed, except in nuclear reactions; see *conservation of energy.*

The principle of CONSERVATION OF MATTER *predicts that the products of any chemical reaction will weigh the same as the combined weights of the reactants.*

conservation of momentum \ˌkän(t)-sər-ˈvā-shən əv mō-ˈment-əm\
PHYSICS. A basic law stating that the velocity and direction of a moving body or moving system not changed by any external force remains constant and is not disturbed by reactions among parts of the body or system.

The law of CONSERVATION OF MOMENTUM *is closely related to Newton's first law, which states that a moving body continues to move in the same direction until acted upon by some force.*



constant \ˈkän(t)-stənt\ *n.*
A relationship that is invariable or not subject to change. The number expressing it may vary, depending on the units used to express the relationship.

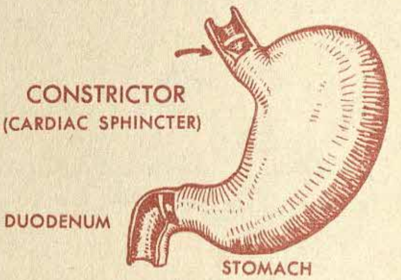
The speed of light in a vacuum is a CONSTANT *that may be expressed as* 3×10^8 *meters per second or as 186,000 miles per second.*

constellation \ˌkän(t)-stə-ˈlā-shən\ *n.*
ASTRONOMY. An apparent group of stars named after an animal, mythical figure or object; also, as used by astronomers, definite areas of the celestial sphere marked off by imaginary boundary lines.

The CONSTELLATION *of Cassiopeia is visible in the northern sky and has the shape of the letter "W."*

constituent \kən-'stich-(ə)wənt\ *n.*
CHEMISTRY. A chemical element that composes part of a substance; also, a part, such as an electron or proton, of an atom.

Chlorine is a CONSTITUENT *of table salt.*

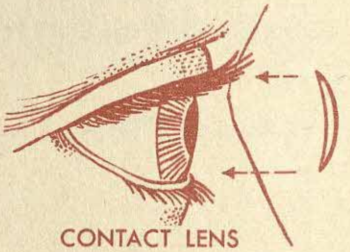


constrictor \kən-'strik-tər\ *n.*
ANATOMY. A muscle that contracts a cavity or opening in the body.

The opening from the esophagus to the stomach is controlled by a CONSTRICTOR *called the cardiac sphincter muscle.*

constructional land form \kən-'strək-shnəl 'land 'fȯ(ə)rm\
EARTH SCIENCE. Land formed by such constructive processes as deposition and volcanic action, rather than by erosion.

The typical structure of a mountain, plateau or plain is that of a CONSTRUCTIONAL LAND FORM.



contact \'kän-ˌtakt\ *n.*
1. ENGINEERING and PHYSICS. A conducting junction between two electrical conductors; also, a special part made to permit such a connection. 2. EARTH SCIENCE. The surface forming the union of two different kinds of rock.

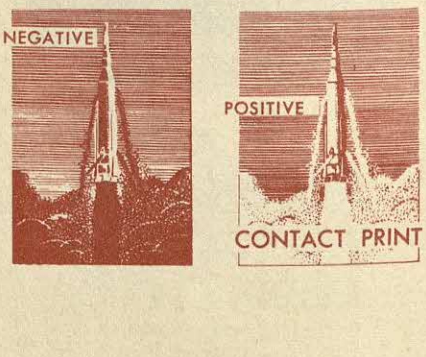
A silver CONTACT *in an electrical switch is desirable because it resists corrosion.*

contact lens \'kän-ˌtakt 'lenz\
MEDICINE. A very small plastic lens fitted next to the eyeball and worn instead of, or in addition to, corrective spectacles.

A CONTACT LENS *will not correct all types of astigmatism.*

contact metamorphism \'kän-ˌtakt ˌmet-ə-'mȯr-ˌfiz-əm\
EARTH SCIENCE. The changes produced in rocks at or near the contact between the rocks and igneous masses.

CONTACT METAMORPHISM *occurs in a relatively-narrow zone around an igneous body.*



contact print \'kän-ˌtakt 'print\
PHYSICS. A positive photographic print made by placing a negative directly on a light-sensitive paper, passing light through the negative and then treating the paper with chemicals.

A CONTACT PRINT *always has the same size as the negative from which it was made.*

contagious \kən-'tā-jəs\ *adj.*

MEDICINE. Referring to a disease that is easily transmitted from one organism to another.

Quarantine is one method of controlling a CONTAGIOUS *disease.*

contaminate \kən-'tam-ə-ˌnāt\ *v.*

To pollute or infect by contact; also, to make a mixture impure; also, to make unfit for a particular use; also, to make potentially injurious or useless because of the presence of radioactive materials.

Disposal of raw sewage in a river will CONTAMINATE *the water.*

CONTINENT
NORTH AMERICA

continent \'känt-ᵊn-ənt\ *n.*

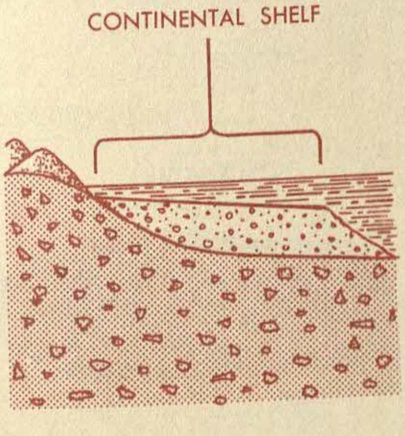
EARTH SCIENCE. One of the six major land masses on the earth's surface: North America, South America, Eurasia, Africa, Australia or Antarctica.

A CONTINENT *generally includes the shallow submerged area, or continental shelf, that surrounds it.*

continental air mass \ˌkänt-ᵊn-'ent-ᵊl 'a(ə)r 'mas\

EARTH SCIENCE. A large, relatively-dry body of air that has originated over a land area.

An arctic CONTINENTAL AIR MASS *may originate in Siberia or northern Canada.*



continental glaciers \ˌkänt-ᵊn-'ent-ᵊl 'glā-shərz\

EARTH SCIENCE. Thick masses of ice covering large areas, as presently found in Greenland and Antarctica; see *ice sheet.*

Several times during the Ice Age, large portions of North America and Europe were covered by CONTINENTAL GLACIERS.

continental shelf \ˌkänt-ᵊn-'ent-ᵊl 'shelf\

EARTH SCIENCE. The zone of shallow ocean floor that gradually slopes from the seashore to an abrupt drop-off.

The deepest part of the CONTINENTAL SHELF *is about 600 feet below sea level.*

continental slope \ˌkänt-ᵊn-'ent-ᵊl 'slōp\

EARTH SCIENCE. The relatively-steep decline from the seaward border of the continental shelf to the ocean deep.

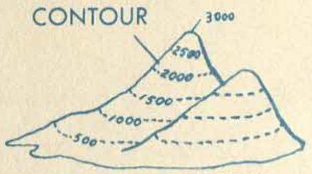
A CONTINENTAL SLOPE *may extend from a depth of about 600 feet to 12,000 or more feet.*

continuous spectrum \kən-'tin-yə-wəs 'spek-trəm\
PHYSICS. An unbroken spectrum produced by incandescent solids or liquids, or gases under high pressure; see *spectrum.*

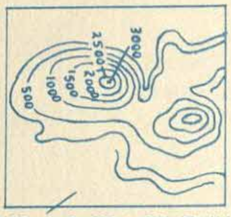
A ball of heated steel produces a CONTINUOUS SPECTRUM.

contour \'kän-ˌtu̇(ə)r\ *n.*
EARTH SCIENCE. On maps and globes, an outline or horizontal representation of the topographical features of a region.

On most maps, the CONTOUR *of a continent or other region is indicated by using a color that contrasts with the color used for an adjacent area.*



MODEL OF MOUNTAIN



CONTOUR MAP OF MOUNTAIN

contour line \'kän-ˌtu̇(ə)r 'līn\
EARTH SCIENCE. A line that connects points having the same elevation above or below sea level.

A CONTOUR LINE *represents how the shoreline would look if the surface of the sea were at that level.*

contractile vacuole \kən-'trak-tᵊl 'vak-yə-ˌwōl\
BIOLOGY. A liquid-filled cavity, or space, in one-celled animals that is associated with the discharge of water from the cell and with the regulation of osmotic pressure.

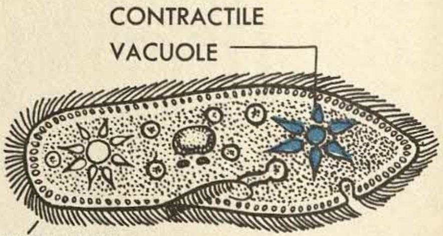
There is a CONTRACTILE VACUOLE *at, or near, both ends of a paramecium.*

contraction \kən-'trak-shən\ *n.*
PHYSIOLOGY. The drawing up and thickening of a muscle or muscle fibers in action.

The CONTRACTION *of heart muscles is a rhythmic action.*

control \kən-'trol\ *n.*
In an experiment, the objects or organisms that are not subjected to some factor or factors that are expected to influence the results, and thus serve as a basis for comparison; a nonexperimental group or object used as a check or means of verifying the results obtained with an experimental group or object.

In testing the effects of a new drug on animals, nondrugged animals are used as a CONTROL.



PARAMECIUM

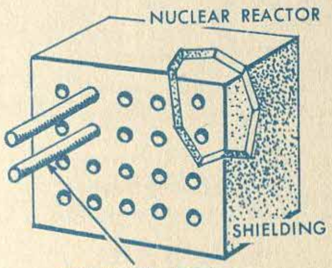
control experiment \kən-'trōl ik-'sper-ə-mənt\
An experiment in which selected factors are allowed to vary, usually one at a time, so that the effect of the variables can be determined.

In a CONTROL EXPERIMENT, *only one factor may be allowed to vary at a given time if the investigator is to be certain that this factor produced a change or influenced the results.*

control rod \kən-'trōl 'räd\

PHYSICS. A rod that is raised or lowered in a nuclear reactor to regulate the rate of reaction by capturing neutrons.

A CONTROL ROD *may be composed of cadmium or boron, metals having the property of absorbing neutrons efficiently without appreciable reradiation.*



CONTROL ROD

control surface \kən-'trōl 'sər-fəs\

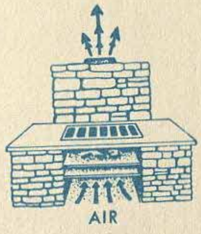
AERONAUTICS. One of the movable surfaces, such as ailerons, elevators or rudders, that are used to change an aircraft's attitude, altitude or speed.

The rudder is a CONTROL SURFACE *used with the ailerons to turn an airplane.*

convection \kən-'vek-shən\ *n.*

PHYSICS. The movement of heated material through a fluid medium, caused by different densities within the medium. Colder, denser material causes warmer, less dense material to rise.

In a freely-falling space capsule, CONVECTION *cannot occur.*



CONVECTION

converge \kən-'vərj\ *v.*

MATHEMATICS. To draw near a meeting point or limit.

In Euclidean geometry, parallel lines never CONVERGE.

convergent evolution \kən-'vər-jənt ˌev-ə-'lü-shən\

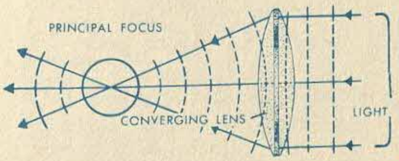
BIOLOGY. The development in different parts of the world of unrelated organisms having similar characteristics.

The North American jack rabbit and the Argentine cavy represent CONVERGENT EVOLUTION.

converse theorem \'kän-ˌvərs 'thē-ə-rəm\

MATHEMATICS. The proposition formed when the hypothesis and conclusion of a given proposition are interchanged.

The proposition that an equilateral triangle is equiangular has the CONVERSE THEOREM *that an equiangular triangle is equilateral.*



CONVERGE

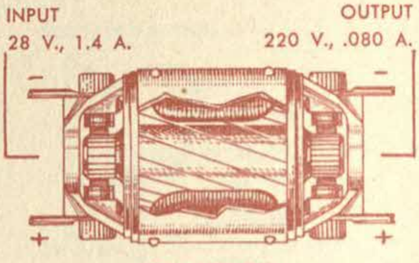
conversion \kən-'vər-zhən\ *n.*

MATHEMATICS. A change in the numerical value of a quantity as a result of changing to a different system of units.

By means of a CONVERSION, *60 miles per hour is found equal to 26.67 meters per second.*

converter \kən-'vərt-ər\ *n.*
1. ENGINEERING. A mechanical device to change alternating current to direct current. 2. CHEMISTRY. An industrial device used in the Bessemer process for making steel.

A CONVERTER *is required for electric motors that operate on direct current when the available power is alternating current.*



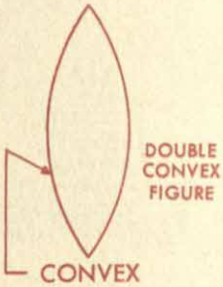
CONVERTER

convertiplane \kən-'vərt-ə-ˌplān\ *n.*
AERONAUTICS. A type of aircraft that can, like a helicopter, take off and land vertically, as well as hover, and that can also fly at higher speeds as a fixed-wing aircraft.

In one type of CONVERTIPLANE, *the conversion from vertical to horizontal flight is made by changing the plane of airscrew rotation from horizontal to vertical.*

convex \kän-'veks\ *adj.*
1. PHYSICS. Curved or rounded, as the surface of a ball seen from the outside; opposite of concave. 2. MATHEMATICS. Referring to any polygon with interior angles equal to or less than 180 degrees.

A glass lens with two CONVEX *surfaces will cause light to focus.*



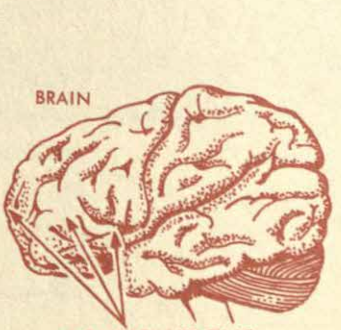
CONVEX

convolutions \ˌkän-və-'lü-shənz\ *n.*
ANATOMY. The ridges or uneven folds on the surface of the brain; also, folds or turns, such as those in the intestines.

As the brain develops, the surface becomes covered with furrows and CONVOLUTIONS.

coordinate \kō-'ȯrd-nət\ *n.*
MATHEMATICS. One of a set of numbers that fixes the position of a point in a line, on a plane or in space with reference to the distance from a fixed point. The set consists of one number for a point on a line, of two for a point in a plane and of three for a point in space.

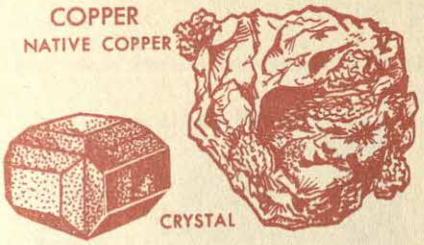
In a plane, the COORDINATE *that designates the distance and direction of the point from the y-axis is called the abscissa of the point.*



CONVOLUTIONS

coordination \(ˌ)kō-ˌȯrd-ᵊn-'ā-shən\ *n.*
PHYSIOLOGY. The harmonious working together of various parts of the body to produce a normal sequence of function of the parts, as in complex movements of the muscles.

The cerebellum, the second largest part of the brain, controls muscular COORDINATION.



coordination compounds \(ˌ)kō-ˌȯrd-ᵊn-'ā-shən 'käm-ˌpau̇ndz\

CHEMISTRY. A group of chemical compounds having a bond between atoms or groups of atoms that have otherwise completed their normal valence requirements.

Both hematin, the substance that gives a red color to blood, and chlorophyll, the substance that gives a green color to plants, are COORDINATE COMPOUNDS.

Copernican system \kō-'pər-ni-kən 'sis-təm\

ASTRONOMY. The theory, stated in the sixteenth century by Nicolaus Copernicus, that the earth is a planet rotating on its axis and revolving around the sun; also, the heliocentric model of the solar system.

The work of Tycho Brahe, Kepler and Galileo helped gain acceptance for the COPERNICAN SYSTEM.

copolymer \(')kō-'päl-ə-mər\ *n.*

CHEMISTRY. A very long, chainlike molecule composed of two alternating subgroups of atoms.

One common type of nylon is a COPOLYMER.

copper \'käp-ər\ *n.*

CHEMISTRY. A metallic element found in its native state and in ores. It is highly ductile and malleable and used principally for electrical wire. Symbol, Cu; atomic number, 29; atomic weight, 63.54.

COPPER *is a component of such alloys as brass, bronze and German silver.*

coquina \kō-'kē-nə\ *n.*

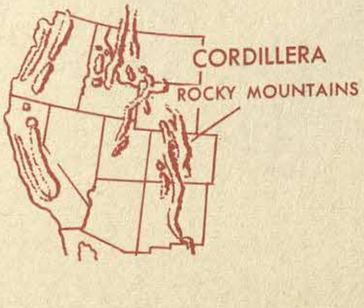
EARTH SCIENCE. A porous limestone rock composed of mollusk shells and coral loosely cemented together.

COQUINA *is a limestone of fairly-recent origin.*

coral \'kȯr-əl\ *n.*

1. EARTH SCIENCE. A rocklike substance consisting of the calcareous skeletons of sea animals and, in tropical waters, forming reefs and atolls. 2. ZOOLOGY. A bottom-dwelling marine coelenterate that frequently grows in colonies.

CORAL *is found in tropical and semitropical seas.*



cordillera \ˌkȯrd-ᵊl-'(y)er-ə\ *n.*

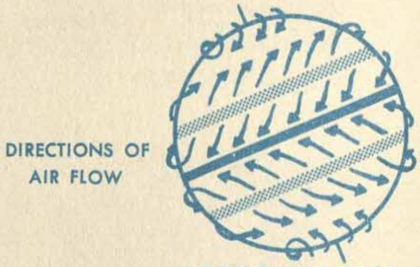
EARTH SCIENCE. A series or chain of mountain ranges.

The Rocky Mountains make up the longest CORDILLERA *in North America.*

core \'kō(ə)r\ *n.*

1. PHYSICS. A piece of metal placed within a coil of wire conducting an electric current to intensify the magnetic effects of the current; also, in a nuclear reactor, the central region containing fissionable material. 2. EARTH SCIENCE. The center of the earth, believed to be in two sections, a solid sphere surrounded by a liquid sphere; also, a cylindrical sample of rock obtained by special hollow drills to gain knowledge of subsurface rocks. 3. BOTANY. The inner, seed-containing portion of such fruits as apples and pears. 4. ZOOLOGY. The hard central portion of the horns of some animals, such as cows.

The CORE *of a transformer is usually made of a stack of electrically-insulated metal plates to decrease energy losses in the form of heat.*



CORIOLIS EFFECT

core memory \'kō(ə)r 'mem-(ə-)rē\

ENGINEERING and MATHEMATICS. In a digital computer, a set of components that store information by certain magnetic combinations as directed by the electronic circuit of the computer.

The capacity of a computer's CORE MEMORY *usually varies with the size of the computer itself.*

Coriolis effect \ˌkōr-ē-'ō-ləs i-'fekt\

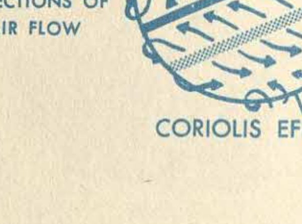
EARTH SCIENCE and PHYSICS. The deflection of a moving mass from a north or south path, caused by rotation of the earth. The effect is most noticeable in such large-scale motions as winds, artillery shells or flowing water.

Winds blowing toward the equator are deflected to the west by the CORIOLIS EFFECT, *while winds blowing from the equator are deflected to the east.*

cornea \'kȯr-nē-ə\ *n.*

ANATOMY and ZOOLOGY. The transparent part of the tough coating of the eyeball that covers the lens and iris.

An injured or diseased CORNEA *may sometimes be replaced by surgically transplanting another cornea.*



corolla \kə-'räl-ə\ *n.*

BOTANY. Flower petals as a unit of structure.

The COROLLA *of a flower surrounds the stamins and pistils.*

corollary \'kȯr-ə-ˌler-ē\ *n.*

MATHEMATICS. In geometry, a statement that requires little or no proof because it follows logically from a previously-proved statement.

Practically any geometric theorem may be followed by a COROLLARY.

corona \kə-'rō-nə\ *n.*

ASTRONOMY. The outermost layer of the sun's atmosphere. It surrounds the chromosphere and is visible as a pearl-white crown or circle when the sun is in total eclipse.

The CORONA *has been observed to extend at least seven million miles from the surface of the sun.*

DURING TOTAL ECLIPSE OF SUN

coronagraph \kə-'rō-nə-ˌgraf\ *n.*

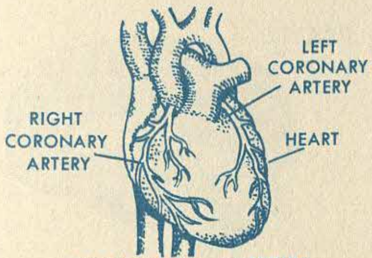
ASTRONOMY. An instrument used to produce an artificial total eclipse of the sun, thus permitting the corona to be photographed without having to wait for the natural total eclipse.

Lenses and diaphragms are used in a CORONAGRAPH *to shut out the light from the photosphere of the sun.*

coronary arteries \'kȯr-ə-ˌner-ē 'ärt-ə-rēz\

ANATOMY. The two arteries that originate in the first part of the aorta and branch to all parts of the heart.

The heart receives a constant blood supply for its own oxygen and nutrition needs through the CORONARY ARTERIES.



CORONARY ARTERIES

corpuscle \'kȯr-ˌpəs-əl\ *n.*

ANATOMY. A protoplasmic particle, such as a red blood cell, a white blood cell or a blood platelet, that has a special function.

A red CORPUSCLE *is also called an erythrocyte, meaning red cell.*

corpuscular radiation \kȯr-'pəs-kyə-lər ˌrād-ē-'ā-shən\

PHYSICS. The conceptualization in which light is supposedly made up of streams of small particles or packages called photons. It is useful in describing light phenomena, such as absorption, heating, reflection and quantum mechanics.

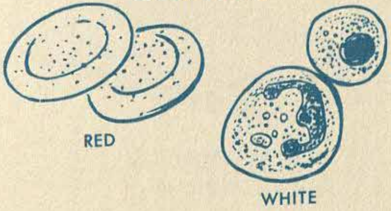
CORPUSCULAR RADIATION *links the motion of light to the motion of small bodies, such as electrons.*

corpuscular theory of light \kȯr-'pəs-kyə-lər 'thē-ə-rē əv 'līt\

PHYSICS. A theory in which light is thought of as a stream of very small particles; a model for light.

The CORPUSCULAR THEORY OF LIGHT *does not satisfactorily explain the refraction of light.*

CORPUSCLE

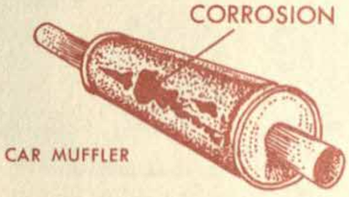


correlation \ˌkȯr-ə-'lā-shən\ *n.*

1. MATHEMATICS. In statistics, a correspondence between two sets of quantities so that an increase in one is accompanied by an increase (positive correlation) or a decrease (negative correlation) in the other; also, in a plane, a transformation of points into lines and lines into points; also, in space, a transformation

of points into planes and planes into points. 2. EARTH SCIENCE. The determination of equivalent or corresponding geologic age in widely-separated outcrops of the same rock formation or in different rock formations of the same age; also, the use of fossil or physical evidence to establish age relationships of rocks or events.

Life insurance experts report a negative CORRELATION *between obesity and life expectancy.*



corrosion \kə-ˈrō-zhən\ *n.*

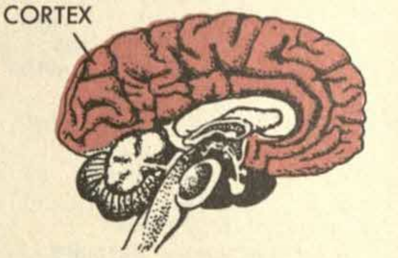
CHEMISTRY. The slow destruction of a material by chemical or electrochemical reaction with its environment.

Rusting, or CORROSION, *of iron requires 40 percent relative humidity before it will occur at normal temperatures in the earth's atmosphere.*

cortex \ˈkȯr-ˌteks\ *n.*

ANATOMY. The outer part, or external layer, of an organ, as distinguished from its inner parts.

The chief motor nerve cells of the cerebral CORTEX *are in the frontal lobe of the brain.*



cortin \ˈkȯrt-ᵊn\ *n.*

PHYSIOLOGY. The secretion from the cortex of the adrenal gland that contains more than one active agent or hormone.

Cortisone is one of the hormones contained in CORTIN.

corundum \kə-ˈrən-dəm\ *n.*

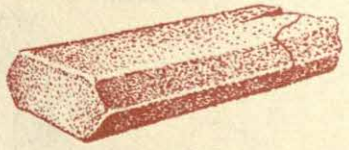
EARTH SCIENCE. A transparent to translucent mineral composed of aluminum oxide, Al_2O_3. In nature, corundum is second only to the diamond in natural hardness and is found in three forms: as a gemstone, as large, crystalline masses and as an impure form called emery.

Ruby and sapphire are gem varieties of CORUNDUM.

cosecant \(ˈ)kō-ˈsē-ˌkənt\ *n.*

MATHEMATICS. In trigonometry, a function of an angle or of a real number that is the radian measure of that angle or of an arc associated with the angle; also, in a right triangle, the function relating either of the acute angles to the ratio of the hypotenuse to the side opposite the angle; *abbr.* csc.

The COSECANT *of an angle of 30 degrees is equal to 2.*



CORUNDUM
(CRYSTAL)

cosine \ˈkō-ˌsīn\ *n.*

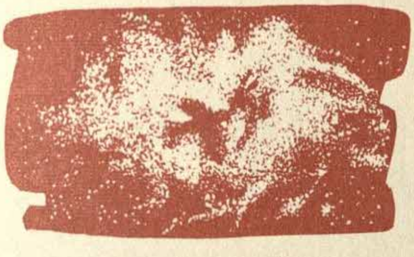
MATHEMATICS. In trigonometry, a function of an angle or of a real number that is the radian measure of that angle or of an arc associated with the angle; also, in a right triangle, the function relating either of the acute angles to the ratio of the side adjacent to the angle to the hypotenuse: *abbr.* cos.

The COSINE *of an angle of 0 degrees is equal to 1.*

cosmic dust \\'käz-mik 'dəst\\

ASTRONOMY. Extremely-fine particles of dust in space.

COSMIC DUST *often obscures the details of interstellar objects, making them difficult to view.*



COSMIC DUST

cosmic rays \\'käz-mik 'rāz\\

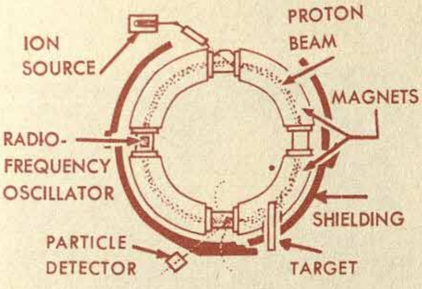
ASTRONOMY and PHYSICS. Radiation that bombards the earth and its atmosphere and that apparently originates in outer space. The *primary* rays enter the atmosphere and collide with atoms of oxygen and nitrogen, thus imparting their energy to *secondary* rays that are detected at lower levels in the atmosphere.

The penetrating power of COSMIC RAYS *must be considered when designing space vehicles and programming space experiments.*

cosmogony \\käz-'mäg-ə-nē\\ *n.*

ASTRONOMY. A branch of astronomy that deals with the origin and development of the universe or any of its parts; also, any theory about such a development.

The most recently-proposed hypothesis of solar system COSMOGONY *is the dust-cloud hypothesis suggested by the American astronomer, Fred Whipple.*



COSMOTRON

cosmology \\käz-'mäl-ə-jē\\ *n.*

ASTRONOMY. The study of the structure of the universe as a whole; also, a theory about the structure of the universe.

The radio telescope, which can be used during both day and night, is playing an important role in gathering evidence which may have importance in COSMOLOGY.

cosmonaut \\'käz-mə-ˌnȯt\\ *n.*

ASTRONAUTICS. A term used in some foreign countries for astronaut. See *astronaut.*

cosmotron \\'käz-mə-ˌträn\\ *n.*

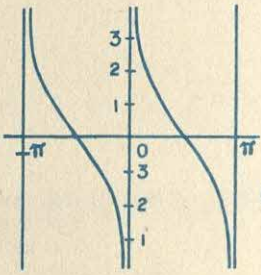
PHYSICS. A device used to accelerate protons to very high speeds, thereby giving the particles energies in excess of one million electron volts.

The COSMOTRON *at Brookhaven National Laboratory in Upton, New York, has been valuable in nuclear research.*

cotangent \\(ˈ)kō-ˈtan-jənt\\ *n.*

MATHEMATICS. In trigonometry, a function of an angle, or of a real number that is the radian measure of that angle, or of an arc associated with the angle; also, in a right triangle, the function relating either of the acute angles to the ratio of the side adjacent to the angle to the side opposite to the angle; *abbr.* cot. or ctn.

The COTANGENT *of an angle, A, is equal to* $\frac{1}{\textit{tangent } A}$.



COTANGENT
(Graph of)

cotyledon \\ˌkät-ᵊl-ˈēd-ᵊn\\ *n.*

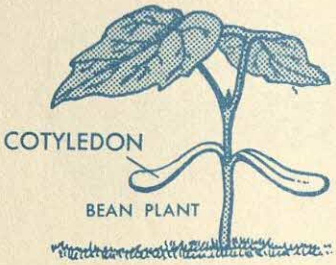
BOTANY. The seed leaf; a small leaflike structure within the seed of a young plant.

Flowering plants may have either one COTYLEDON *or two.*

coulomb \\ˈkü-ˌläm\\ *n.*

PHYSICS. A standard amount of electrical charge equal to the number of electrons passing a given point in a conductor in one second when a current of one ampere is flowing.

A COULOMB *of negative charge contains* 6.24×10^{18} *electrons.*



Coulomb's law \\ˈkü-ˌlämz ˈlȯ\\

PHYSICS. A mathematical relationship describing the force of attraction or repulsion between two charged objects. The amount of force depends on the magnitude of the charges and the distance and material separating them.

COULOMB'S LAW *may be applied to forces between magnetic poles.*

coulometer \\kü-ˈläm-ə-tər\\ *n.*

PHYSICS. An electrolytic cell used to measure the amount of electric charge moving through a circuit.

In a COULOMETER, *one coulomb of electric charge will deposit exactly 0.000329 grams of copper metal from solution.*

counter \\ˈkau̇nt-ər\\ *n.*

PHYSICS. A device that measures the intensity of ionizing radiation. It is composed of two main parts: the detector that converts ionizing radiation to electric pulses, and the counter proper that records the pulses.

A Geiger-Muller COUNTER *is more effective in measuring beta radiation than alpha or gamma radiation.*

counterbalance \\ˈkau̇nt-ər-ˌbal-ən(t)s\\ *n.*

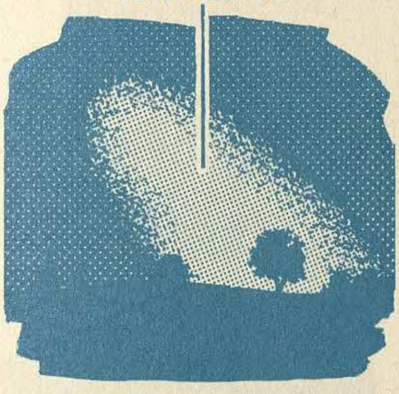
1. ENGINEERING. A weight, usually applied to an unbalanced moving part to offset vibration, wear and friction caused by

inertia. 2. PHYSICS. A force used to neutralize the effect of another force by opposing that force.

Centrifuges used to test man's ability to withstand g-forces are constructed with a COUNTERBALANCE *that undergoes the same effects as the test gondola and its passenger.*

counterglow \'kau̇nt-ər-ˌglō\ *n.*
ASTRONOMY. An elliptical glow on the ecliptic opposite the sun, thought to be caused by the reflection of sunlight from small particles in space; also called gegenschein.

COUNTERGLOW *is not seen easily but may be photographed with wide-angle cameras.*


COUNTERGLOW

covalent bond \(')kō-'vā-lənt 'bänd\
CHEMISTRY. One kind of force that holds atoms together in a molecule; also, the attraction between atoms that share one or more pairs of electrons.

In a water molecule, a COVALENT BOND *exists between each of the two hydrogen atoms and the oxygen atom.*

covalent compound \(')kō-'vā-lənt 'käm-ˌpau̇nd\
CHEMISTRY. A compound in which atoms are bonded together to form molecules by sharing pairs of electrons.

If a substance is a liquid or gas at room temperature, it is probably a COVALENT COMPOUND.

Crab Nebula \'krab 'neb-yə-lə\
ASTRONOMY. A cloud of gases with the outline of a crab located in the constellation Taurus. It is now identified as the debris of a supernova whose occurrence was recorded by the Chinese A.D. 1054.

The CRAB NEBULA *appears as a faint star to the naked eye.*

CRAB NEBULA

cracking \'krak-iŋ\ *n.*
CHEMISTRY. A process used for breaking large molecules into smaller molecules and frequently applied to large hydrocarbon compounds of crude oil in order to increase the yield of gasoline. The process utilizes heat, pressure and usually a catalyst.

CRACKING *may double the amount of gasoline obtained from a barrel of crude oil.*

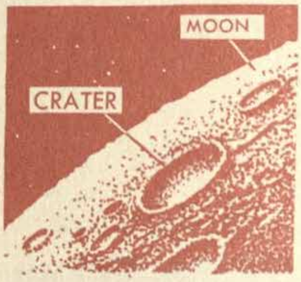
cranial \'krā-nē-əl\ *adj.*
ANATOMY. Referring to the skull or the part of the skull covering the brain.

Some of the CRANIAL *nerves are completely sensory, while others contain motor as well as sensory fibers.*

cranial cavity \'krā-nē-əl 'kav-ət-ē\

ANATOMY. The space inside the skull, taken up mostly by the brain.

The cerebellum is in the CRANIAL CAVITY.



cranium \'krā-nē-əm\ *n.*

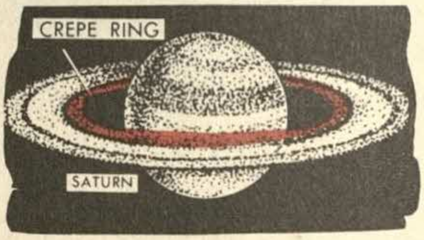
ANATOMY. The part of the skull that covers the brain.

The adult human CRANIUM *consists of eight bones joined together by means of dovetailed, immovable joints.*

crater \'krāt-ər\ *n.*

1. EARTH SCIENCE. A steep-sided, bowl-shaped, roughly-circular pit at the summit of a volcano; a volcanic basin having a diameter of less than three times its depth; also, the depression formed by a meteorite striking the earth. 2. ASTRONOMY. One of the saucerlike depressions on the surface of the moon.

A CRATER *may form when ejected material forms a ring around a volcanic opening or when the summit of a volcano collapses.*



CREPE RING

creosote \'krē-ə-ˌsōt\ *n.*

CHEMISTRY. An odorous oil obtained by the distillation of wood tar or coal tar.

Wood fence posts and railroad ties may be treated with CREOSOTE *to retard decay.*

crepe ring \'krāp 'riŋ\

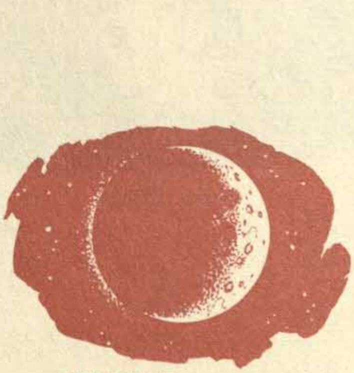
ASTRONOMY. The innermost, hazy, almost transparent ring encircling the planet Saturn.

The light of stars may shine through the CREPE RING.

crescent \'kres-ᵊnt\ *adj.*

ASTRONOMY. Referring to the moon or to any of certain planets when some, but less than half, of the object appears to be illuminated.

The CRESCENT *moon between new moon and first-quarter moon appears in the western half of the sky at sunset.*



CRESCENT

crevasse \kri-'vas\ *n.*

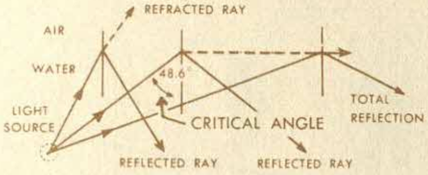
EARTH SCIENCE. A deep, vertical crack or fissure in a glacier; also, a wide crack in the levee of a stream or canal.

A CREVASSE *forms as a result of stresses produced when adjacent areas of a glacier move at different speeds.*

critical altitude \\'krit-i-kəl 'al-tə-ˌt(y)üd\\

AERONAUTICS. The height above the earth's surface at which a plane's engine ceases to operate efficiently.

Below CRITICAL ALTITUDE, *a supercharger can maintain in the intake manifold of an engine a pressure equal to that existing when the engine operates at sea level.*



CRITICAL ANGLE

critical angle \\'krit-i-kəl 'aŋ-gəl\\

PHYSICS. The smallest angle of incidence (the angle between the light rays and a perpendicular to the surface between the two substances) at which reflection of all the light takes place as light passes from one transparent substance into another.

The CRITICAL ANGLE *for water to air measures about 48 degrees.*

critical mass \\'krit-i-kəl 'mas\\

PHYSICS. The smallest amount of fissionable material that is capable of sustaining a chain reaction without an external source of neutrons.

When a CRITICAL MASS *of fissionable material is assembled in a nuclear reactor, control rods prevent the reaction from producing enough energy to cause an explosion.*

critical pressure \\'krit-i-kəl 'presh-ər\\

PHYSICS. The minimum pressure needed to liquefy a gas at its critical temperature.

The CRITICAL PRESSURE *of carbon dioxide may be obtained at room temperature.*

CRO-MAGNON MAN

critical temperature \\'krit-i-kəl 'tem-pər-ˌchu̇(ə)r\\

PHYSICS. The maximum temperature at which a gas can be liquefied by pressure.

When a gas is above its CRITICAL TEMPERATURE, *it cannot be turned to liquid by any amount of pressure.*

critical volume \\'krit-i-kəl 'väl-yəm\\

PHYSICS. The volume occupied by one mole of a substance at its critical temperature and critical pressure.

Avogadro's law does not apply to the CRITICAL VOLUME *of gases.*

Cro-Magnon man \\krō-'mag-nən 'man\\

ZOOLOGY. A prehistoric race of man that lived on the European continent during the retreating phase of the last glacier.

Paintings, tools, and skeletal remains of CRO-MAGNON MAN *have been found in caves in France.*

Crookes tube \\'krůks 't(y)üb\\

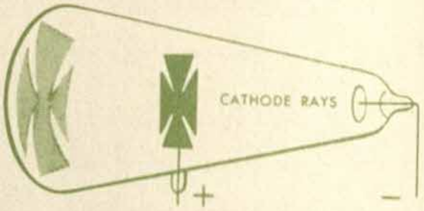
PHYSICS. A high-vacuum tube having a sealed electrode at each end. The electrodes are connected to an external source of voltage and the space between the electrodes is used to study the movement of free electrons.

Wilhelm Roentgen discovered X rays as a result of his experiments with a CROOKES TUBE.

crossbreeding \\'kròs-ˌbrēd-iŋ\\ *n.*

BIOLOGY. The mating of parents having greatly-different genetic characteristics, usually resulting in an offspring that has unique features.

A mule is the result of CROSSBREEDING *a female horse and a male donkey.*



CROOKES TUBE

crosscutting relationships \\'krò-ˌskət-iŋ ri-'lā-shən-ˌships\\

EARTH SCIENCE. A basic rule establishing the age relationship between a younger rock and other rocks that it cuts across.

CROSSCUTTING RELATIONSHIPS *are used to determine the relative age of igneous rocks that are intruded or cut into sedimentary rocks.*

crossing-over \\ˌkrò-siŋ-'ō-vər\\ *n.*

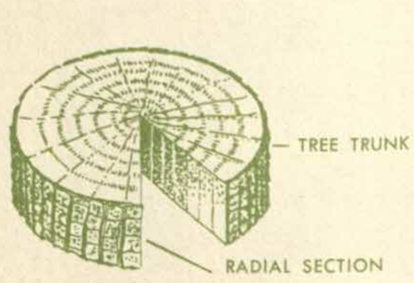
BIOLOGY. The exchange of genes between two paired chromosomes during meiosis, resulting in unexpected combinations of linked genes within the gametes.

Distances between genes of a chromosome can be estimated by determining the number of times that CROSSING-OVER *occurs.*

cross-pollination \\ˌkrò-ˌspäl-ə-'nā-shən\\ *n.*

BOTANY. The transfer of pollen from a stamen of one flower to the pistil of another flower of the same species by natural or artificial means.

The wind, bees and birds are natural carriers of pollen in the CROSS-POLLINATION *of many flowers.*

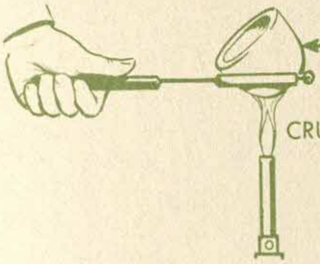


CROSS SECTION

cross section \\'kròs 'sek-shən\\

1. MATHEMATICS. A crosswise slice or cut of a material at right angles to an axis or plane; also, a small group representative of a much larger group. 2. EARTH SCIENCE. A profile and vertical section of the earth's crust drawn from data obtained by geologic and geophysical exploration. 3. PHYSICS. The probability of a collision between a bombarding particle and an atomic nucleus, usually referred to as nuclear cross section.

The number of growth rings found in a CROSS SECTION *of a tree trunk is a basis for determining the tree's approximate age.*



crucible \'krü-sə-bəl\ *n.*

CHEMISTRY and ENGINEERING. A cup-shaped container in which metals or other substances may be melted or heated when high temperatures are required. It is usually made of such refractory materials as porcelain, graphite or clay.

A porcelain laboratory CRUCIBLE *will crack if heated or cooled too suddenly.*

crust \'krəst\ *n.*

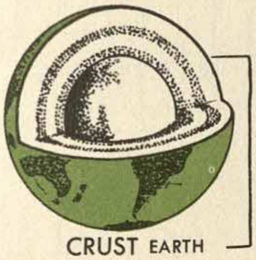
EARTH SCIENCE. The outer layer, or shell, of the earth, 20 to 30 miles thick, made up of granite and basalt; see *lithosphere.*

The CRUST *of the earth is thicker under the continents than it is under the oceans.*

cryogenics \,krī-ə-'jen-iks\ *n.*

PHYSICS. The study and production of very low temperatures and their associated phenomena.

The techniques developed in CRYOGENICS *have achieved temperatures within 1/1,000 of a degree of absolute zero.*



crystal \'krist-ᵊl\ *n.*

EARTH SCIENCE. An homogeneous solid whose atoms have a definite arrangement; also, a characteristic geometric shape of a solid resulting from the orderly internal arrangement of its atoms.

Because of its definite internal structure, a CRYSTAL *can be identified by X-ray diffraction.*

crystal lattice \'krist-ᵊl 'lat-əs\

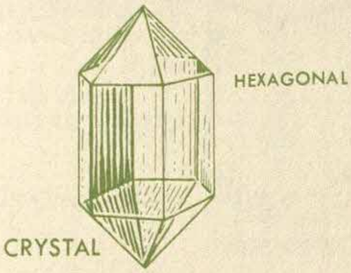
CHEMISTRY. The three-dimensional pattern in which atoms arrange themselves as a substance assumes crystalline form; also, the geometrical relationship between the atoms in a crystal.

Diamond is very hard because its carbon atoms are tightly bound together in a CRYSTAL LATTICE *of interlocking cubic forms.*

crystalline \'kris-tə-lən\ *adj.*

CHEMISTRY and EARTH SCIENCE. Describing a solid substance having the properties of a crystal; also, describing particles that are usually hard or glossy.

Salt and ice are CRYSTALLINE *substances when below their melting temperatures.*



crystallization \,kris-tə-lə-'zā-shən\ *n.*

CHEMISTRY. The process by which a substance forms crystals from a molten or gaseous state or from a saturated solution.

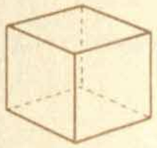
Evaporating the water from a salt solution will result in the CRYSTALLIZATION *of salt.*

crystallography \ˌkris-tə-'läg-rə-fē\ *n.*
PHYSICS. The study of the external and internal characteristics and structures of crystals.

CRYSTALLOGRAPHY *has contributed to the development of new alloys of metals.*

crystalloids \'kris-tə-ˌlȯidz\ *n.*
CHEMISTRY. Substances that will dissolve in water and that can be crystallized. When dissolved, crystalloids will diffuse through a membrane.

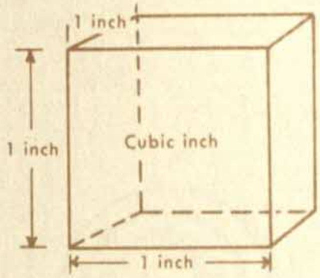
Sugar and salt are both CRYSTALLOIDS.



CUBE

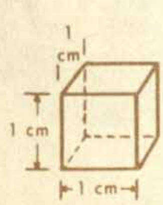
cube \'kyüb\ *n.*
MATHEMATICS. A solid with six congruent square faces; also, the third power of a number, or the result obtained when a given number is used as a factor three times. For example, the cube of 3 is 3 times 3 times 3, or 27.

The intersecting edges of a CUBE *are perpendicular to each other.*



cube root \'kyüb 'rüt\
MATHEMATICS. The number that, when used as a factor three times, results in a given number (for example, since 64 equals 4 times 4 times 4, 4 is the cube root of 64).

In advanced mathematics classes, students learn that a number has more than one CUBE ROOT.



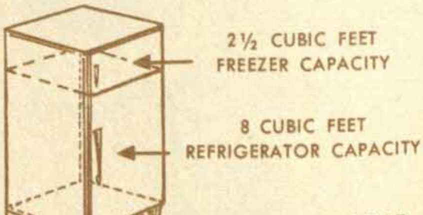
CUBIC CENTIMETER

cubic centimeter \'kyü-bik 'sent-ə-ˌmēt-ər\
MATHEMATICS. A unit of volume equal to the space enclosed by a hollow cube that has an inside length, width and height of one centimeter; nearly equivalent to one milliliter; *abbr.* cc.

A CUBIC CENTIMETER *of water at a certain temperature will always have the same weight, but the weight of the same volume of sugar may vary, depending on how tightly it is packed.*

cubic equation \'kyü-bik i-'kwā-zhən\
MATHEMATICS. An equation of one variable in which three is the highest power, or exponent, of the variable.

The expression $5x^3 + 2x^2 + 7x + 12 = 0$ *is a* CUBIC EQUATION.



CUBIC MEASURE

cubic measure \'kyü-bik 'mezh-ər\
MATHEMATICS. The system of cubic units used to measure the volume of a solid geometric figure.

The capacity of a refrigerator is given in CUBIC MEASURE *as a number of cubic feet.*

culture \\'kəl-chər\\ *n.*

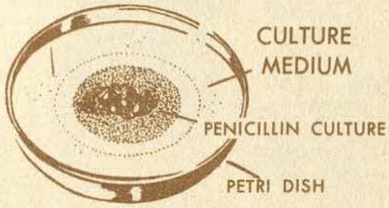
BIOLOGY and MEDICINE. Bacteria or other microorganisms on a culture medium; see *culture medium.*

A CULTURE *that contains only one species of bacteria is called a pure culture, while one that contains more than one species is called a mixed culture.*

culture medium \\'kəl-chər 'mēd-ē-əm\\

BIOLOGY and MEDICINE. Any material in which microorganisms find nourishment and in which they can reproduce.

A CULTURE MEDIUM *may contain finely-ground meat mixed with water, together with peptone and common salt.*



cumulonimbus \\ˌkyü-myə-lō-'nim-bəs\\ *adj.*

EARTH SCIENCE. Referring to a massive cloud, with great vertical development, whose top is in the shape of an anvil and often has a fibrous texture; a thundercloud.

The CUMULONIMBUS *cloud is usually associated with rain or snow, sometimes with hail and often with thunderstorms.*

cumulus \\'kyü-myə-ləs\\ *adj.*

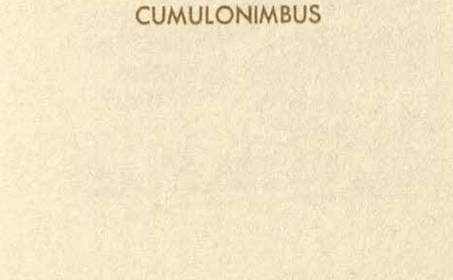
EARTH SCIENCE. Referring to a thick, fleecy cloud that has vertical development, a rounded top and sides and a flat base.

The CUMULUS *cloud develops during fair weather as a result of warm, moist air rising by convection.*

cupric \\'k(y)ü-prik\\ *adj.*

CHEMISTRY. Referring to any copper compound in which the copper ions have a valence, or oxidation state, of plus 2.

The common name for CUPRIC *sulfate is blue vitriol.*



CUMULONIMBUS

cuprite \\'k(y)ü-ˌprīt\\ *n.*

EARTH SCIENCE. A mineral composed of cuprous oxide, Cu_2O; copper ore.

CUPRITE *may occur in crystalline form as a fine-grained aggregate or as a massive rock.*

curie \\'kyü(ə)r-(ˌ)ē\\ *n.*

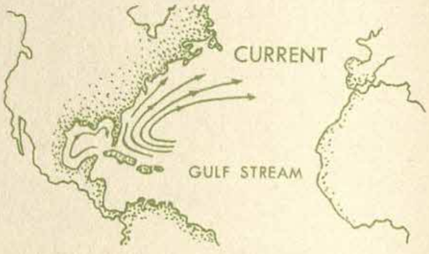
PHYSICS. A unit of radioactivity equal to the quantity of any radioactive substance that undergoes 3.7×10^{10} nuclear disintegrations per second.

One gram of pure radium is approximately equal to one CURIE *of radioactivity.*

curium \'kyu̇r-ē-əm\ *n.*

CHEMISTRY. A man-made, radioactive element that does not occur naturally on earth. Symbol, Cm; atomic number, 96; atomic weight, 238 to 249, depending upon the isotopes.

Seaborg, Jones and Ghioso first produced CURIUM *in 1942 by bombarding plutonium 239 with alpha particles.*



current \'kər-ənt\ *n.*

1. EARTH SCIENCE. A flow of water or air in a definite direction. 2. PHYSICS. A flow or movement of electrical charges.

The Gulf Stream is an ocean CURRENT *flowing at an average speed of about four miles per hour.*

current density \'kər-ənt 'den(t)-sət-ē\

PHYSICS. The rate of electrical current flow through a square centimeter (or other unit of area) of conducting material.

In electroplating chromium on steel, a high CURRENT DENSITY *is desirable.*

CURRENT RIPPLE MARKS

current ripple marks \'kər-ənt 'rip-əl 'märks\

EARTH SCIENCE. A pattern of marks, similar to rows of very small sand dunes or hills, that is made by current action on the bottom of a stream or body of water. The marks are asymmetrical, or different on each side.

CURRENT RIPPLE MARKS *indicate the direction in which the stream was flowing at the time of deposition.*

cuspids \'kəs-pədz\ *n.*

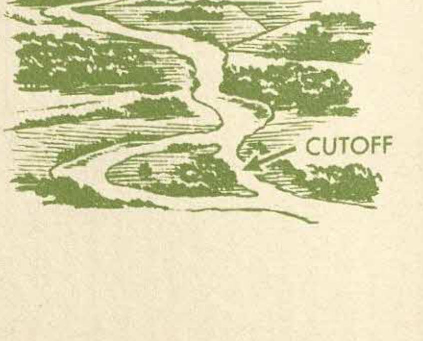
ANATOMY and ZOOLOGY. Single-pointed teeth located on each side of the mouth between the front cutting teeth, or incisors, and the molars; canine teeth.

The CUSPIDS *of a meat-eating animal are used to tear food.*

cuticle \'kyüt-i-kəl\ *n.*

1. ANATOMY and ZOOLOGY. A skin, membrane or hard covering of a cell or organ, produced by the epidermal cells; also, in man and the higher animals, the outer epidermal layer at the base and sides of fingernails and toenails. 2. BOTANY. A thin, waxy, waterproof layer covering the outer surfaces of the leaves of some plants; a cutin layer.

A cross section of human hair exhibits an outside layer, or CUTICLE, *a cortex layer and a central row of cells.*



cutoff \'kət-ˌȯf\ *n.*

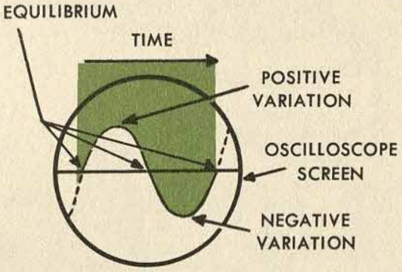
EARTH SCIENCE. A new course made by a stream when it cuts across the neck of a horseshoe-shaped bend in its channel.

An oxbow lake may result from a CUTOFF.

cybernetics \ˌsī-bər-ˈnet-iks\ *n.*

The study of animal control systems and mechanical or electronic control systems in relationship to each other; for example, the feedback and interaction between information-control-information in the muscle-nerve-brain system in man and the mechanical-electronic system in the automatic pilot of an airplane.

The bat's system of echo ranging could be the starting point for a research project in CYBERNETICS.



CYCLE
(alternating current)

cycle \ˈsī-kəl\ *n.*

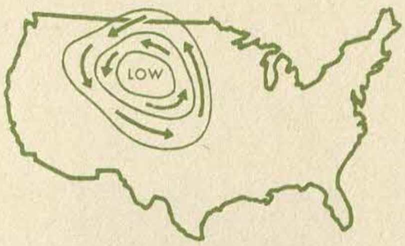
1. PHYSICS. In wave phenomena, a series of events starting with equilibrium and going through positive variation, equilibrium and negative variation, ending with equilibrium; also, a unit used to express a sound or radio-wave frequency. 2. BIOLOGY. A series of developmental stages in the life histories of plants and animals. 3. MATHEMATICS. In a set of ordered elements, the advance of each member by one position so that the last member replaces the first; also, a permutation of a set of elements that gives a circular arrangement of the members whereby a change is brought about by having each element advance one position. 4. A series of events that always occur in the same order and usually are repeated regularly.

The CYCLE *of an alternating current wave is shown on an oscilloscope when the wave is converted into a light image.*

cycle of erosion \ˈsī-kəl əv i-ˈrō-zhən\

EARTH SCIENCE. The successive changes in river valleys and other surface features as erosion wears down land to a base level. The three main stages are youth, maturity and old age.

The CYCLE OF EROSION *represents a total period of time during which erosion takes place.*



CYCLONE

cyclone \ˈsī-ˌklōn\ *n.*

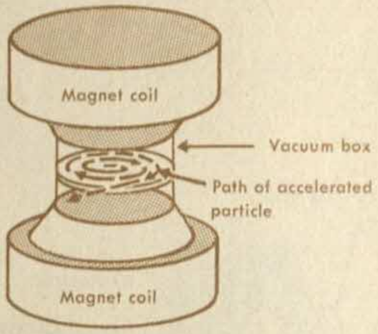
EARTH SCIENCE. A region of low atmospheric pressure in which winds move spirally inward toward the center, with the direction of spiral movement being counterclockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere.

A CYCLONE *is usually referred to as a "depression" or "low" in Temperate zones and as a "tropical cyclone" in the equatorial zone.*

cyclotron \ˈsī-klə-ˌträn\ *n.*

PHYSICS. A device to bombard atomic nuclei, having at its center the two halves of a cylindrical box placed between the poles of a powerful electromagnet. The halves are evacuated and alternately charged by an oscillator. Protons, deuterons and other charged particles are consequently accelerated in a spiral path from the center to a high energy level at the outside, where they bombard atomic nuclei.

The CYCLOTRON, *the third type of particle accelerator developed, was preceded by the Cockroft-Walton voltage multiplier and the Van de Graaff electrostatic generator.*



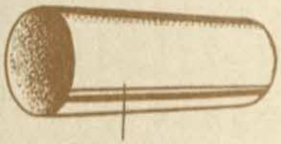
CYCLOTRON

cylinder \\'sil-ən-dər\\ *n.*
MATHEMATICS. A solid formed by a closed cylindrical surface; also, the sections formed by two parallel planes cutting all the elements of a closed cylindrical surface.

To find the volume of a CYLINDER, *multiply the area of its base by its altitude.*

cyst \\'sist\\ *n.*
1. MEDICINE. A sac without an opening that develops in a natural cavity or an organ of the body and contains diseased material, either liquid or semisolid in nature. 2. BIOLOGY. Any of a number of saclike structures formed in plants or animals; also, a resting stage in the life cycle of certain plants and animals.

A CYST *may develop around a foreign body within the organs or tissues of an organism.*



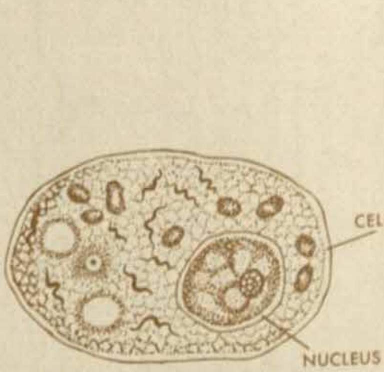
CYLINDER

cytochrome \\'sīt-ə-,krōm\\ *n.*
BIOLOGY. A red, iron-containing pigment, structurally related to the red, iron-containing heme of hemoglobin in blood; also, one of a group of hydrogen carriers in aerobic respiration.

A protein substance containing iron atoms and called a CYTOCHROME *is present in every living cell.*

cytogenetics \\,sīt-ə-jə-'net-iks\\ *n.*
BIOLOGY. The branch of biology that deals with heredity through the study of genes, chromosomes and cell division.

The study of CYTOGENETICS *developed from cytology, the study of cells, and from genetics, the study of inheritance.*



CYTOPLASM

cytology \\sī-'täl-ə-jē\\ *n.*
BIOLOGY. The branch of biology that deals with the form, structure, function, behavior, chemistry and life cycle of living cells.

A microscope is an important tool in the study of CYTOLOGY.

cytoplasm \\'sīt-ə-,plaz-əm\\ *n.*
BIOLOGY. The protoplasm that surrounds the nucleus in a cell.

Chloroplasts are found in the CYTOPLASM *of a leaf cell.*

D

Daltonism \\'dȯl-tən-iz-əm\\ *n.*

MEDICINE. Color blindness; particularly, difficulty in distinguishing between red and green; see *color blindness.*

Because the gene for DALTONISM *is recessive and also located in the X chromosome, color blindness is more common in men than in women.*

Dalton's law \\'dȯl-tənz 'lȯ\\

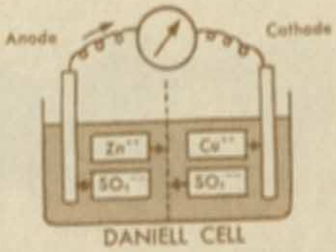
CHEMISTRY. The statement that given quantities of gases mixed together exert the same pressure as the total of the pressures exerted by each gas independently; also known as Dalton's law of partial pressures.

DALTON'S LAW *holds true only within certain temperature and pressure ranges and in cases where no chemical reaction takes place.*

damp \\'damp\\

1. PHYSICS (V.). To decrease the amount of oscillating (back-and-forth) motion. 2. CHEMISTRY (N.). An explosive gas, or combination of gases, found frequently in coal mines; see *firedamp.*

Dragging feet will quickly DAMP *the back-and-forth motion of a playground swing.*



DANIELL CELL

damping \\'dam-piŋ\\ *n.*

PHYSICS. A process by which a decrease in back-and-forth motion is accomplished; also, the progressive approach of an oscillating system to steady, or motionless, equilibrium.

DAMPING *may be observed in the movements of a needle indicator on the scale of an instrument as it vibrates in smaller and smaller arcs before coming to rest.*

Daniell cell \\'dan-yəl 'sel\\

PHYSICS. A primary electric cell in which a zinc plate is immersed in zinc sulfate solution, and a copper plate is immersed in copper sulfate solution. The two solutions are separated by a porous material that allows only the ions to pass through. The zinc is the anode and the copper is the cathode.

A DANIELL CELL *produces an electromotive force of about 1.1 volts.*

dark-field illumination \'därk-ˌfēld il-ˌü-mə-'nā-shən\

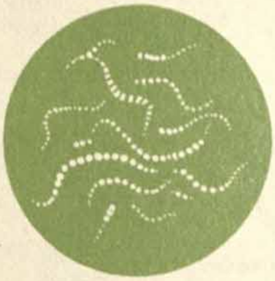
PHYSICS. A method of illuminating an object under a microscope in such a way that no direct light reaches the objective lens other than the light that is refracted, diffracted or scattered by the object itself.

DARK-FIELD ILLUMINATION *makes visible transparent, unstained material and very small objects that are invisible under normal microscopic illumination.*

dark-line spectrum \'därk-ˌlīn 'spek-trəm\

PHYSICS. A spectrum in which certain narrow bands of color are replaced by dark lines. The phenomenon occurs when light emitted from hot gases or an incandescent solid passes through cooler gases and certain frequencies of light absorbed by the cooler gases appear as dark lines in the spectrum.

Scientists use a DARK-LINE SPECTRUM *to analyze the chemical composition of the cooler outer layers of the sun and other stars.*



DARK-FIELD ILLUMINATION

BACTERIA

dark nebula \'därk 'neb-yə-lə\

ASTRONOMY. A mass of gas or finely-divided matter in space, so isolated that it does not reflect light from stars. It can be detected only by its darkening effect on luminous bodies or on other bright nebulae beyond it.

The famous Horsehead Nebula in the constellation of Orion is a DARK NEBULA.

dark star \'därk 'stär\

ASTRONOMY. A star so faintly luminous that it is almost invisible; also, a star that has no luminosity.

In the case of a pair of eclipsing variables, the DARK STAR *is the star being eclipsed.*

DARK NEBULA

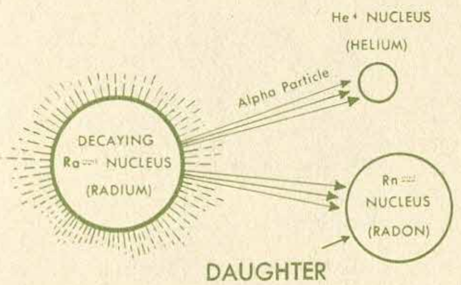
Darwinism \'där-wə-ˌniz-əm\ *n.*

BIOLOGY. The theory of evolution advanced by Charles Darwin. The theory states that all species of plants and animals develop from earlier forms by a process known as natural selection According to the theory, successive generations produce offspring with characteristics slightly different from their own. Individuals whose characteristics best suit their environments survive and reproduce, and, after many generations, a new species may be produced through this process.

An application of DARWINISM *is found in the theory of radiative adaptation, that gives one explanation for the origin of new kinds of plants and animals.*

date line \\'dāt 'lin\\

A shortened term for international date line. See *international date line.*



DAUGHTER ELEMENT

daughter cell \\'dȯt-ər 'sel\\

BIOLOGY. A new cell produced by the division of an older one.

A DAUGHTER CELL *is, with rare exception, an exact duplication of its parent.*

daughter element \\'dȯt-ər 'el-ə-mənt\\

PHYSICS. The element, or nucleus, that is the immediate result of a nucleus undergoing radioactive decay.

Radon, the DAUGHTER ELEMENT *of radium, produces its own daughter element, polonium.*

day \\'dā\\ *n.*

ASTRONOMY. A unit of time determined by one rotation of the earth; also, commonly, the time from dawn until dark; see *lunar day, sidereal day* and *solar day.*

The solar DAY *of 24 hours is approximately the length of time between two successive passages of the sun across a meridian.*

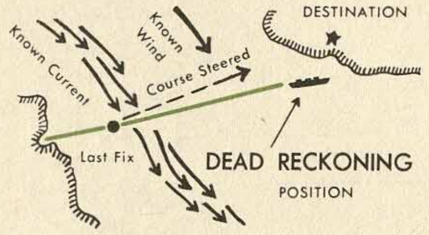
DC

An abbreviation for direct current. See *direct current.*

DDT

CHEMISTRY. A colorless, odorless insecticide; an abbreviation for dichloro-diphenyl-trichloroethane.

Some species of insects may become resistant to the effects of DDT.



DEAD RECKONING POSITION

dead reckoning \\'ded 'rek-(ə-)niŋ\\

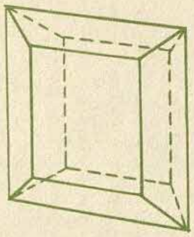
AERONAUTICS. A method of navigating by the calculation of position and course, based on time, speed, estimated drift and other variables.

When a pilot loses radio or radar contact, he must figure his position and course by DEAD RECKONING.

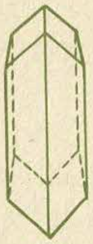
decagon \\'dek-ə-ˌgän\\ *n.*

MATHEMATICS. A polygon having ten sides.

The construction of a regular DECAGON *in a circle requires the division of the circle's radius in extreme and mean ratio.*



DECAHEDRON



SIDE VIEW

decahedron \\ˌdek-ə-'hē-drən\\ *n.*

MATHEMATICS. A polyhedron or solid figure having ten faces.

Precious stones are sometimes cut in the form of a DECAHEDRON.

decantation \ˌdē-ˌkan-ˈtā-shən\ *n.*

CHEMISTRY. Pouring a liquid so that sediment in the bottom of the container is not disturbed.

DECANTATION *is often used in chemical analysis to separate a precipitate from the liquid in which it formed.*

DECANTATION

decay \di-ˈkā\ *n.*

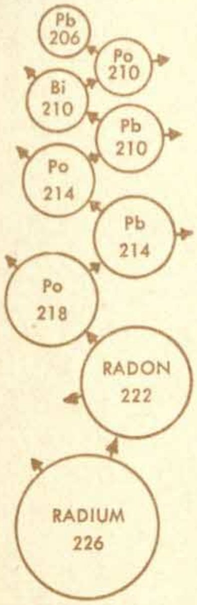
1. PHYSICS. A process that results in a decreased force, quantity or activity; also, the energy-releasing transformation of one radioactive element to another element that may or may not be radioactive; generally, any spontaneous disintegration of a nucleus to form a simpler nucleus by emitting alpha, beta or gamma radiation, or some combination of the three. 2. BIOLOGY. The breakdown of dead organic substances by microorganisms. 3. ASTRONAUTICS. The slowing of an orbiting satellite caused by atmospheric friction.

Alpha radiation accompanies the DECAY *of radium to radon.*

decay rate \di-ˈkā ˈrāt\

PHYSICS. The natural rate at which radioactive elements are transformed into other elements by energy-releasing nuclear processes; frequently expressed in terms of half-life.

Experiments have shown that the DECAY RATE *for radioactive elements is not changed by raising or lowering temperature.*



DECAY SERIES

decay series \di-ˈkā ˈsi(ə)r-(ˌ)ēz\

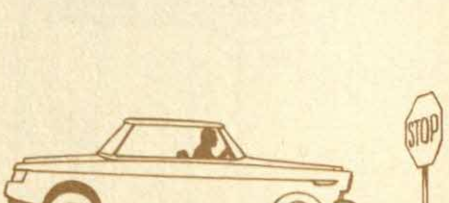
PHYSICS. A series of elements, each resulting from the radioactive decay of the one before it, and each succeeding member of the series being an isotope resulting from the emission of some type, or combination of types, of radiation.

Lead is the end product of the DECAY SERIES *starting with uranium 238.*

deceleration \(ˌ)dē-ˌsel-ə-ˈrā-shən\ *n.*

ASTRONAUTICS and PHYSICS. A decrease in the speed of a moving body, usually expressed as a rate of decrease.

The DECELERATION *of an automobile depends on road conditions, type of tires, efficiency of brakes and other factors.*



DECELERATION

decibel \ˈdes-ə-ˌbel\ *n.*

PHYSICS. A unit of power used in comparing intensities of electrical or sound energies with an arbitrary standard and equal to $\frac{1}{10}$ bel.

The smallest change in loudness the human ear can detect is approximately one DECIBEL.

DECIDUOUS

deciduous \di-'sij-ə-wəs\ *adj.*

1. BOTANY. Describing plants that lose their leaves annually. 2. ZOOLOGY. Describing animals that shed such things as antlers and hair periodically or such things as wings and teeth at a particular stage of growth.

The trees and shrubs whose tops and roots survive through the winter are divided into two groups, the DECIDUOUS *group and the evergreen group.*

decimal fraction \'des-ə-məl 'frak-shən\

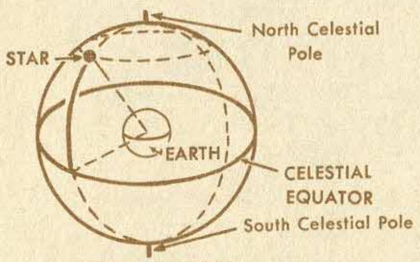
MATHEMATICS. A fraction whose denominator is a power of ten. In common notation, the denominator is omitted but is indicated by a decimal point to the left of as many digits as there are zeros in the denominator.

The DECIMAL FRACTION $\frac{495}{100}$ *is usually written as 4.95, while* $\frac{23}{1,000}$ *is written as .023.*

decimal system \'des-ə-məl 'sis-təm\

MATHEMATICS. A system of counting or of numeration in which ten is used as the base.

The mileage indicator in a car uses the DECIMAL SYSTEM *to indicate the distance the car has traveled.*

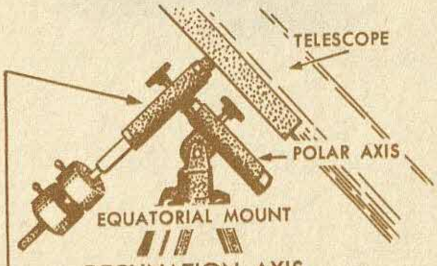


DECLINATION

declination \ˌdek-lə-'nā-shən\ *n.*

1. ASTRONOMY. The angular measure of a star's distance from the celestial equator calculated on a great circle that passes through the celestial pole and the star. 2. EARTH SCIENCE. The angle between a compass needle pointing toward magnetic north and a line indicating true north.

An astronomer can locate any stellar object if he knows its DECLINATION *and right ascension.*



DECLINATION AXIS

declination axis \ˌdek-lə-'nā-shən 'ak-səs\

ASTRONOMY. The axis (one of two) of an equatorial telescope mounting that is located at right angles to the polar axis and that allows the barrel of a telescope to be moved in a direction perpendicular to the celestial equator.

The circle on the DECLINATION AXIS *of a telescope mounting measures degrees of declination.*

decompose \ˌdē-kəm-'pōz\ *v.*

CHEMISTRY. To break up into simpler compounds or elements by chemical reaction.

Water will DECOMPOSE *into hydrogen and oxygen if heated to a high-enough temperature.*

decomposer \ˌdē-kəm-ˈpōz-ər\ *n.*

BIOLOGY. An organism or substance that causes the breakdown of complex compounds into elements or simpler compounds. Bacteria, molds and fungi in the soil are the decomposers that cause decay of dead plant and animal materials.

The action of a DECOMPOSER *returns nutrients to the soil in forms that can be reused by green plants.*

decompression \ˌdē-kəm-ˈpresh-ən\ *n.*

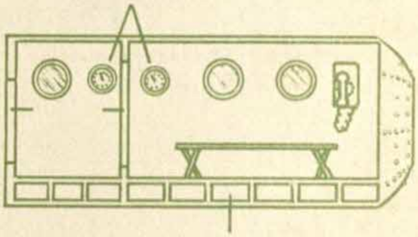
PHYSICS. The process of decreasing pressure.

Divers emerging from deep water must undergo gradual DECOMPRESSION *to prevent the dissolved nitrogen in their blood from forming bubbles.*

decompression chamber \ˌdē-kəm-ˈpresh-ən ˈchām-bər\

ENGINEERING. An enclosure constructed so that the pressure inside can be reduced gradually. Its function may be to go from high pressures to normal atmospheric pressure or from atmospheric pressure to very low pressures.

Divers breathing a mixture of helium and oxygen do not ordinarily need to use a DECOMPRESSION CHAMBER *after emergence, since such a mixture does not contain the bubble-forming nitrogen found in pure air.*



DECOMPRESSION CHAMBER

decontaminate \ˌdē-kən-ˈtam-ə-ˌnāt\ *v.*

To remove radioactive material from a specific area; also, to remove a poisonous substance from an area.

Special procedures are required to DECONTAMINATE *a laboratory if radioactive materials are accidentally spilled.*

decrement \ˈdek-rə-mənt\ *n.*

1. PHYSICS. The relative change in amplitude of two successive oscillations as damping occurs. 2. MATHEMATICS. A decrease from a given number; also, a negative increment, or a decrease in the numerical value of a variable.

The DECREMENT *of a freely-swinging pendulum is less each time it swings.*

decuple \ˈdek-yə-pəl\ *n.*

MATHEMATICS. An amount ten times larger than another number; tenfold.

Ten is the DECUPLE *of one.*

deduct \di-ˈdəkt\ *v.*

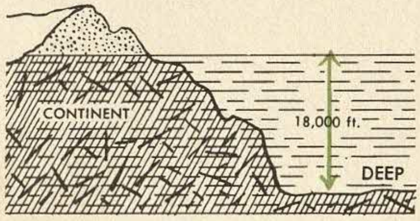
MATHEMATICS. To subtract one amount from another.

If we DEDUCT *7 from 8, the result is 1.*

deduction \di'dək-shən\ *n.*

A method of reaching a conclusion based on certain premises or statements in which reasoning moves from general ideas to specific examples; also, that which is deduced; also, the process of taking away from or subtracting, or that which is taken away.

If the general properties of the group of inert elements are known, the properties of a particular member of the group, such as helium, can be predicted by DEDUCTION.



DEEP

deductive method \di-'dək-tiv 'meth-əd\

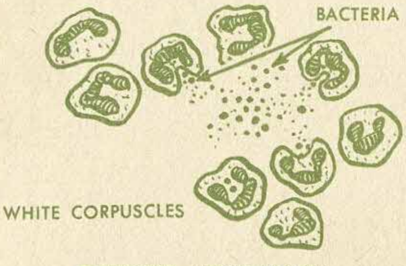
A process of reasoning in which specific conclusions or applications are drawn from general rules or premises.

The DEDUCTIVE METHOD *is used in geometry to proceed from such generalities as definitions, axioms and postulates to the solution of a particular problem.*

deductive proof \di-'dək-tiv 'prüf\

MATHEMATICS. A proof based upon the deductive method of reasoning; a sequence of statements proceeding from the hypothesis or hypotheses of a theorem to its conclusion, each statement being supported by a previously-proved theorem or assumption.

Most theorems of plane geometry are verified by DEDUCTIVE PROOF.



DEFENSE MECHANISM

deep \'dēp\ *n.*

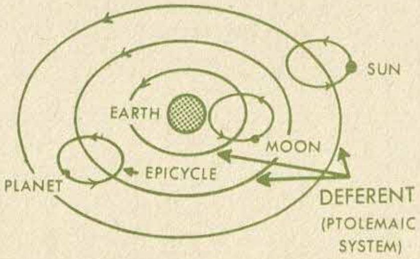
EARTH SCIENCE. Any area on the floor of the sea that is more than 18,000 feet below the surface.

A DEEP *may be detected by measuring the length of time it takes for a sound wave to be reflected from the ocean floor back to the surface.*

defense mechanism \di-'fen(t)s 'mek-ə-ˌniz-əm\

BIOLOGY and PHYSIOLOGY. A means by which an organism defends itself against infection by microorganisms.

The process in which white blood cells destroy germs within a wound is a DEFENSE MECHANISM.



DEFERENT

deferent \'def-(ə-)rənt\

1. ASTRONOMY (N.). In the earth-centered Ptolemaic system, one of several concentric circles on which it was believed the moon, sun and planets moved; see *epicycle.* 2. ANATOMY (Adj.). Referring to a duct, tube or nerve that carries fluid or an impulse away from an organ or a part; opposite of efferent.

In the Ptolemaic system, the moon, sun and each planet had its individual DEFERENT.